Department of Mechanical Engineering
University of Canterbury

Energy Constraint and Adaptability: Focus on Renewable Energy on Small Islands

A thesis submitted in partial fulfilment of the
requirements for the Degree of
Ph.D. in Mechanical Engineering
at the University of Canterbury
by
Muaviyath Mohamed

University of Canterbury
2012

Abstract

Renewable energy integration into diesel generation systems for remote island communities is a rapidly growing energy engineering field. Fuel supply issues are becoming more common and the disruption, instability and panic caused by fuel shortages results in inefficient and unreliable power supplies for remote island communities. This thesis develops an energy engineering approach for meeting renewable energy development, supply security, cost and sustainability objectives.

The approach involves adapting proven energy engineering techniques including energy auditing, energy system modelling with basic cost analysis and demand side management. The novel aspect of this research is the development of critical load engineering in the system design, and informing this with an assessment of essentiality of energy services during the audit phase. This approach was prompted by experiences with previous fuel shortages and long term sustainability policy drivers.

The methodology uses the most essential electric loads as the requirement for sizing the renewable energy capacity in the hybrid system. This approach is revolutionary because communication with the customers about availability and the need to shed non-essential loads helps to both meet cost and security requirements and to reduce levels of panic and uncertainty when fuel supply issues arise.

A sustainable power generation system is a system that provides continuity of supply for electrical appliances that are considered by the residents to be essential and for which adaptability and resilience of behaviour were key design priorities over growth. The sustainable electrical energy supply should match the critical (essential) load and should have the ability to continue without major disruptions to the daily lives of the people in these communities. Essential energy end uses were identified through energy audits and surveys. The electric power system is designed so that renewable energy sources alone can meet that “essential” demand with a plant that is both economically and technically feasible. Diesel generators were supplemented to meet the short fall in meeting the unconstrained electric demand. This is to design a system that is generally competitive with the present conventional power generation. This method should be particularly suitable for handling the complexities of a modern-day energy system in terms of planning a sizable sustainable energy and electricity system, either based on wholly sustainable sources or integrating sustainable sources of energy into a conventional generation system.

The final hybrid system chosen after numerous simulations for the case study (Fenfushi island in the Maldives) community has the minimum renewable energy sources to meet the essential load but uses diesel to supplement the present load. A variety of design parameters such as PV size, wind turbine sizes and numbers and battery capacity have been considered. The minimum renewable energy sources to supply the essential loads of the community were simulated with diesel generators to find the optimal supply mix for the present load (typical unconstrained demand). The final outcome has the following characteristics: NPC and COE were $1,532,340 and $0.37/kWh respectively, lower than any diesel-only systems that could supply the demand. The total annual electricity production is 386,444 units (kWh), of which 9.61% is excess electricity and the annual operating cost is $68,688. Compared to the diesel-only systems there is a fuel savings of 77,021 litres of diesel per year, which is a 66.5 % reduction. An annual carbon dioxide emission reduction of 202,824 kg was achieved, which is a reduction of 66.5%. An annual renewable energy contribution of 70% would be achieved, 34% of which would be from PV arrays and 36% from wind turbines. The selected system shows that even with 30 percent power supply from diesel generators, still the highest NPC is on diesel generation for a life of over 25 years.

Acknowledgements

I would like to thank God, for His guidance and strength.

I would like to thank my senior supervisor, Associate Professor Susan P. Krumdieck for the unique ideas, support, guidance and encouragement she provided during the course of this research. The foundation for this work comes from her insightful ideas and her ability to think beyond the boundaries of what is currently accepted. I would also like to thank her for all her technical support of me attending conferences, which provided me with ideal opportunities to present my work and meet experts in the field and the chance to acquaint myself with new research dimensions from around the world. I also genuinely thank my second supervisor, Dr Larry Brackney, for his vast knowledge and experience. This contributed immensely in our discussions and was always productive. Despite their busy schedules, it was amazing how quickly they responded to my forwarded documents. I would not have completed this work without their help. I really appreciate the time and effort you gave towards my research. Your comments on my drafts were invaluable. Thanks to Dr. Ee-hua Wong for advice on structure and last-minute editorial advice.

This thesis was made possible through a scholarship from the New Zealand government, under the New Zealand Development Aid (NZAID) programme—a Commonwealth scholarship. It is my duty and great pleasure to express gratitude to these parties. I thank the administration of the University, especially the International Student Support Unit (ISSU), for their timeless support throughout my time in New Zealand.

I have come a long way from home to study here at the University of Canterbury. Nevertheless, during my study towards a PhD degree, I have experienced the warm hospitality and invaluable suggestions of many people and have enjoyed many new activities; I would like to express my appreciation to the many people who have welcomed me in this acknowledgement.

Advanced Energy and Material Systems Laboratory members and, most notably, my office mates have been a great source of practical information and the small Maldivian community here in Christchurch was helpful in every possible way. Because so many people have assisted me along the way, I cannot mention every name; however, I really do appreciate each and every one of you.

I would like to dedicate this thesis to my beloved parents, for their hard determined work in bringing me up and for encouraging higher education. They have always been there for me and have made me what I am today. Furthermore, I express my deepest and most sincere gratitude to my wife Fanna, for her understanding and patience throughout my time here; without her support I would not have reached this stage. My appreciation stretches to my loving children Inan, Shayan and Yuh, for their patience. I simply could not have done this without them by my side. I also thank all my family members and friends for their encouragement and support.

Publications/Presentations from this Thesis

1. Mohamed, M. and Krumdieck, S., Energy Constraint and Adaptability: Focus on Renewable Energy on Small Islands. NERI, National Energy Research Institute in partnership with the Institute of Earth Science and Engineering at The University of Auckland on November 22 and 23 2007 with the theme: 'Research informing the energy debates'. New Zealand, Auckland Conference 2007.

2. Mohamed, M.,Krumdieck, S., and Brackney, L., Solar and Wind Energy for Small Island Electrification: A Maldivian Case study, UKERC, UK Energy Research Centre, Parkstead House, Roehampton, London, 23-27 June 2008.

3. Mohamed, M., Krumdieck, S., and Brackney, L., Integration of Renewable Energy for Remote Island Communities and Resiliency under Energy Constraint, NERI, National Energy Research Institute, New Zealand, Knowing More, Doing Better conference, Rutherford House, Wellington, April 2009.

4. Mohamed, M., Krumdieck, S., and Brackney, L., Essentiality of Electrical Energy Demand and Integration of Renewable Energy for Sustainable Generation System: Remote Island Case Study, College of Engineering, University of Canterbury, New Zealand, 2009.

5. Mohamed, M., Krumdieck, S., and Brackney, L., Sustainable Renewable Electricity for Small Islands: A Methodology for Essential Load Matching, NZSSES, The New Zealand Society for Sustainability Engineering and Science, Transitions to Sustainability Conference, Auckland, December 2010.

6. Mohamed, M., Krumdieck, S., and Fulhu, M., A Methodology to Develop Sustainable Electricity for Small Rural Communities: Supply System Design for Critical Load Matching. EEA (Electricity Engineers' Association) Conference & Exhibition 2011, Sky city Convention Centre, 23-24 June, Auckland.

7. Mohamed, M., Krumdieck, S., Brackney, L., (2011). An Energy Auditing Methodology for Small Island Communities. *Journal of Environmental Science and Engineering*, David publishing company, accepted for publication, May 2011.

8. Mohamed, M., Krumdieck, S., (2011). Renewable Energy Resource Assessment of the Maldives for Electric Power Generation. *Journal of Environmental Science and Engineering*, David publishing company, *accepted* for publication, May 2011.

9. Mohamed, M., Krumdieck, S., Brackney, L., (2011). A Methodology to Develop Sustainable Electricity for Small Rural Communities: Supply System Design for Critical Load Matching. *Journal of Environmental Science and Engineering*, David publishing company, accepted for publication, May 2011.

10. Mohamed, M., Krumdieck, S., (2011). Assessment Criteria for Small Scale Decentralized Electric Power Generation Systems: A Case Study for the Island of Fenfushi in the Maldives. *Journal of Environmental Science and Engineering*, David publishing company, accepted for publication, May 2011.

11. Mohamed, M., Krumdieck, S., (2011). Water Desalination for Small Island Communities from Sustainable Electrical Energy. *Journal of Environmental Science and Engineering*, David publishing company, accepted for publication, June 2011.

Table of Contents

Table of Figures

List of Tables

Chapter 1

Introduction

1.1 Introduction

The common practice in designing electric power systems in small rural islands is to design a system that has the capacity to supply the peak load when the peak load is known (Abdel-Aal 2006; Biczel & Koniak 2011; Hammons 2008; Hatziargyriou et al. 2007; Onar et al. 2008). On most of the islands in the Maldives (case study in this research is based on an island in the Maldives), customers are not restricted from using electrical appliances of their choice. Hence, the designed power system supplies unrestricted power to the end users. For those islands with smaller generator sets with restricted appliances and limited hours of electricity, the norm in designing power capacity is to follow the other islands with similar population. The same rule is being followed in designing systems with renewable resources but this will make the system prohibitively expensive as the upfront investment requirement for renewable systems are very expensive compared to conventional systems. Conventional power systems are designed for large centralised generation and there is very little or no consumer participation; no proper communication between the consumers and the supplier (Orecchini & Santiangeli 2011).

The state of the art in the field of rural small island electrification is about the smart grids with renewable energy sources, that incorporates various components necessary for a smart grid:

- Using automatic controlling mechanisms to control and switch over between components when necessary in the generation and distribution of power, accommodating bi-directional power flows, allowing renewable energy resource management, distributed generation management, optimisation of DSM (demand side management), optimisation of storage management and coordination of local energy management and integration of conventional and renewable energy resources (Crossley & Beviz 2010; Faruqui et al. 2009; Flick & Morehouse 2011; Järventausta et al. 2010; Orecchini & Santiangeli 2011; Wissner 2011b).

- Effective use of information and communication technology (ICT) in reducing peak demand based on signals like system security, price increase and environmental impact of peaking fossil generation is an area of growing interest. Enhance right decision making ability from both supply and demand side to operate power systems: as right information is necessary for right decisions (Gyamfi 2010; Heidell & Ware 2010; Jackson 2010; Nair & Zhang 2009; Wissner 2011a,b).

- Methods for forecasting daily peak loads to a number of days ahead has also attracted many researchers (Amjady & Daraeepour 2009; Azadeh & Faiz 2011; Bayón et al. 2009; Catalão et al. 2011; Diongue et al. 2009; Lin et al. 2010a,b; Meng & Niu 2011; Pedregal & Trapero 2010; Shafie-khah et al. 2011; Singhal & Swarup 2011; Sumer et al. 2009; Taylor 2010).

- Proper system balancing methodologies with high levels of intermittent renewable sources, as the penetration levels of renewable sources increase, more advanced control of the power system will be required. Hence, many operations at present manage by humans to replace with machines for quicker response time and for efficient process of large quantities of data (Andersen & Lund 2007; Barton & Gammon 2010; Battaglini et al. 2009; Hammons 2008; Pillai et al. 2011; Pouresmaeil et al. 2011; Stadler 2008).

1.2 The Contribution of this Work

In this thesis a new methodology is proposed in designing sustainable rural island power generation systems (grids), which have the capacity to supply the critical/essential load of the community. The designed system should be able to provide this critical load with all renewable resources. The essential design load of the community is identified by means of a "human adaptive survey". A "human adaptive survey" is a survey to categorise the existing loads according to their essentiality to the people, identify the impact that would have on them from each of these loads for their well being, extent of adaptability with each of these loads. This information leads to a load curve which is very much less than the typical load of the community. Designing a system with renewable sources for critical load is significantly economical compared to a system design for the typical load. The final outcome would be an unconstrained power grid/supply making an allowance for diesel generators to compensate where renewable power short falls to meet the typical load. Key advantages of this system would be:

- Considerably less capital intensive compared to all renewable sources for typical load (actual load curve)
- Overall cost of energy falls, even in comparison with diesel only systems
- Energy security is guaranteed for critical loads
- Under normal circumstances there would be no restrictions to consumer power utilisation
- Preventing the island communities from total collapse of their power generation system in an event where diesel supply is disrupted as they (the islands in the Maldives) have experienced two severe and many minor disruptions during the past twenty years.

Even though the methodology developed does not account ways of sending signal to the customers, when to restrict their power consumption and by how much/level, under constraint situations a signal or message to restrict their consumption should be practical for the system to supply restricted essential loads without system failure. The signalling component is not included for two reasons: It would not be difficult in a constrained situation to send a general message to every household as these islands are small. Even now the islands have their own ways of sending messages to the residents, such as by mega phones and on public notice boards. Designing a sophisticated metering protocol to inform every individual household would itself be a major project and is beyond the anticipated work.

The proposed methodology incorporates levels of human adaptability under energy constraints, island energy auditing, renewable resource prospecting, energy system modelling and demand side management. This method is demonstrated in a detailed study of the current electric power system, and electricity generation options with two levels of constraints to the conventional fuel supplies for a remote island community in the Republic of Maldives. The selected island community fairly represents the majority of the nearly 200 inhabited islands in the republic. These islands are ideally suited for testing new methodologies due to the simple nature of the existing power generation systems and their vulnerability to any fossil fuel supply shortages. Special emphasis is given to the level of adaptability in fuel supply constraint scenarios. The potential of renewable energy for electric power generation in the future is explored within the different levels of constraint and adaptability of the community residents. **The key contribution of this thesis is setting up a design**

load, incorporating human adaptability in electrical power utilisation under constrained situations. The concept uses an appropriate electricity power generation system with renewable sources that will meet the essential electric load of the community. In other words, the aim is to find a sustainable electricity generation system for island communities.

1.3 Motivation

Increasing energy demand and the problems associated with utilising energy from fossil fuels in the fragile environment of the small coral islands are driving efforts to develop alternative sources of energy and ways to reduce the consumption of fossil fuels. The islands of the Maldives are blessed with abundant renewable energy (RE) resources, most notably solar and wind, but have become overwhelmingly dependent on petroleum imports for electricity production (van Alphen & Hekkert 2008). Petroleum products account for more than 16% of the expenditure on imported goods to the country in 2004 (van Alphen et al. 2007) and this trend is increasing with the living standard of the general public. Current technology and infrastructure are designed to utilise low cost, abundantly available fossil energy. However, world oil production is expected to peak in the near future (Aftabuzzaman & Mazloumi 2011; Aleklett et al. 2010; Deffeyes 2001a; Gallagher 2011; Hirsch 2008; Kontorovich 2009; Maggio & Cacciola 2009; Owen et al. 2010; Voudouris et al. 2011). Anthropogenic climate change is another of the many problems associated with the consumption of fossil fuels. These two factors ensure that fossil fuel systems cannot continue to operate as they have, with the current patterns of unlimited fossil energy and continuous growth.

Energy audits of buildings and other facilities have shown that opportunities to save and conserve a substantial amount of energy and electricity use do exist (AlQdah 2010; Batty & Probert 1989; Chaudhary et al. 2009; Doukas et al. 2009; Gordic et al. 2010; Hong et al. 2010; Kabir et al. 2010; Li et al. 2010). To date, no energy audit of these islands has been performed to assess the level of adaptability of the residents and, as far as we are aware of, no appropriate method has been developed to perform energy audits of smaller island communities such as the ones in the Maldives to account human resiliency to electric power. Based on the literature produced by various studies in other parts of the world, we are convinced that formulating and engineering methodology to perform energy audits in small island settings would be beneficial (Pfeiffer et al. 2005; Sendegeya et al. 2006; Soratana & Marriott 2010; Zhu 2006). The identification of a way to optimise the use of existing diesel generators and finding alternative ways of meeting substantial demand without further increasing the generation from the diesel generators would be particularly useful. Energy auditing and energy management could, potentially, save the country importing thousands of barrels of fossil fuel and help avoid the attendant emissions and local air, water and noise pollution.

Local impacts of diesel fuel contamination and pollution are particularly acute on small islands, as land is very limited and there is no “out of the way” place to locate a power station and a fuel storage facility. The global environmental effects of fossil fuel use are disastrous for small island nations as the climate changes and sea levels rise; these shifts will have negative implications and catastrophic results. Using less fossil energy will lead to a more sustainable energy system for these islands. Fluctuations in the fuel price (specifically diesel) will directly impact local households. The impact will be especially dire in the Maldives, due to the impending privatisation of the national electricity generation system. Electricity generation on these islands has been heavily subsidised by the government in recent years, meaning that consumers do not have a full understanding of its real price. The 2007-2009 fuel price shock was particularly detrimental to the Maldives, which relies on diesel fuel for literally everything it needs to survive—for fresh water production, sewage pumping, all transport, and nearly all electricity and for the functioning of its primary industry of international tourism. Impending resource shortages are imposing constraints on energy infrastructure systems, but these constraints have not yet been recognised within regional energy planning processes.

1.4 Overview of the Thesis – Thesis Organization

A literature review is carried out in Chapter 2 as a way of background that places this work in context and sets out the theoretical frame for this thesis; the meaning of sustainability is defined within the context of this research, as is the theory of continuity. Krumdieck's theoretical model of anthropogenic continuity is introduced and discussed, and the location at which this research is based is demonstrated and further clarified in the model. Chapter 3 explains the proposed methodology, identifying the appropriate levels of renewable energy within the system to design constrained power system and presenting these in the *Sustainable Energy System Design Method*-method developed in this thesis. Every step in the model is explained in detail.

Field survey results are presented in Chapter 4. Chapter 4 presents the results of domestic and commercial energy surveys and surveys of the energy supply and distribution systems on the island. As a contrast, their (the case study) energy resources are then assessed in Chapter 5. Among the areas investigated are solar energy potential and the wind power situation in different parts of the country, based on the recorded data at local weather stations.

The methodology is then applied to the case study island, Fenfushi, in the Maldives and is discussed in Chapter 6. All the technical details of the system configurations modelled for the case study are presented in Chapter 6. The final decision making criteria as they relate to risk are presented in Chapter 7 and a supply system suitability index developed by considering important factors from the simulated results is presented in Chapter 7 as well, as a means of decision making. Each step of the risk analysis method is covered in depth, and the analysis is presented in detail. A summary of the risk analysis results and of the system suitability index are presented. Chapter 8 presents a discussion of the methodology; the results of the case study and the conclusions, with opportunities for future research in this field.

Chapter 2

Background

This chapter explores developments in energy engineering and sustainability, with a particular emphasis on remote and small communities. Some specific examples of the challenges energy engineering faced for remote communities will be discussed. Energy engineering schemes adopted by some islands and remote communities around the world are reviewed and the sustainability of these communities electrical energy systems is explored. Developments in sustainable energy engineering will be addressed. The concept of global peak oil based on the geological findings and their possible occurrence period along with the finite nature of the fossil fuel will be discussed. Krumdiecks' model of the regional energy – environment – economy system will be explored to explain the importance of multidisciplinary approach in designing regional energy systems.

2.1 Energy Engineering

Energy engineering is a term that is broadly used across a range of different engineering disciplines that deal with energy efficiency, energy services, facility management, plant engineering, environmental compliance and alternative energy technologies. Energy minimization is the purpose of this growing discipline. Often applied to building design, heavy consideration is given to HVAC, lighting and refrigeration, with the objective being to both reduce energy loads and increase the efficiency of current systems (Mitchell 1983; Sørensen 2004). Energy Engineering is increasingly seen as a major step forward in meeting carbon reduction targets (Atkins et al. 2010; Friedler 2010; Gaggioli 1983; Gumerman et al. 2001; Hsu et al. 2011; Jiang & Tovey 2010; Lee et al. 2009; Liu et al. 2010; Nakata et al. 2011; Ortolano 1984; Shenoy 2010; Strachan & Kannan 2008; Thumann & Mehta 2001; Van Heddeghem et al. 2011). Energy Technology refers to the knowledge of and usage skills required for the conversion, production, transfer, distribution and use of energy. Technology is mastered based on the laws of nature and thus forms of energy can be used to serve the needs of mankind in a way that both spares nature and takes the economic resources of society into consideration.

The study of energy and its relationship with the environment is a relatively new and rapidly growing area within the field of sustainability engineering; research institutions across the world are branching into this sphere. The burning of fossil fuels releases carbon dioxide and other noxious gases and particles into the atmosphere and the adverse effects of this on climate change has drawn much attention worldwide (particularly to the issues of global warming and rising sea levels). Energy engineering originally referred to the discipline of designing electrical power supply systems to match an existing or forecasted electricity demand (Kowalski et al. 2009). A booming economy after World War II encouraged the exponential growth of energy consumption in Western countries. Energy engineering reached a turning point only after the 1973-1974 OPEC (Organization of the Petroleum Exporting Countries) oil embargo, when the field expanded to include the demand for new technologies to improve energy efficiency (Turner & Doty 2006; Weston 1992). The analysis of both supply and demand is generally referred to as energy systems engineering.

2.1.1 Developments in Energy Engineering

The real developments in energy engineering for conservation, efficiency and end use management occurred after the OPEC oil embargo of 1973-1974. There was a significant boost in research into demand and supply management with an aim to save energy and increase efficiency. This led to the development of Reference Energy Systems (RES) to capture the energy flows and conversions (Aydinalp-Koksal & Ugursal 2008; Hammond 2000; Marcuse et al. ; Williams 2001). These RES can easily be transformed into mathematical models such as MARKAL: A description of MARKAL is given in Appendix E.

Advances in energy engineering are providing engineers with a state-of-the-art education in the area of advanced energy technologies and systems. These are based on an original and equilibrated combination of process systems engineering and electrical engineering disciplines.

An interdisciplinary problem-solving approach is necessary for identifying sustainable solutions in the energy sector. More precisely, energy engineers learn how to design, develop and implement energy systems and technologies in various sectors of society while efficiently managing energy issues (Alam Hossain Mondal et al. 2010; Azzaro-Pantel et al. 2008; Dinica et al. 2007; Liu et al. 2009; Lund 2010; Subhash & Satsangi 1990; Yamaguchi et al. 2007). Significant developments in energy engineering may lead to a sustainable energy development. Seven major areas have specific problems in relation to sustainable energy development. Among these are the following areas: energy resources and development, efficiency assessments, clean air technologies, information technologies, new and renewable energy resources, environment capacity, mitigation of nuclear power threat to the environment (Afgan et al. 1998; Destatte 2010; Dincer 2000; Karakosta & Askounis 2010; Lior 2010; Omer 2008; Shailaja 2000; Streimikiene et al. 2007).

2.1.2 Remote Systems

On many small and remote islands, there is a significant electrical power shortage and many supply interruptions occur; there are many places that are unlikely to ever be connected to a main grid network due to cost and geographic issues. The operation cost of autonomous thermal power stations is very high due to the many challenges and constraints on these remote islands. Hunter and Elliot identify three broader applications of remote electrical power, namely (Hunter & Elliot 1994):

- power for specialized applications in remote areas, e.g. communications, irrigation
- power for remote communities in industrialized countries and on islands
- community power generation in developing countries

Lundsager identifies two general methods of rural energy supply: grid extension and the use of diesel generators (Ardehali 2006; Lundsager).

Renewable energy sources such as wind and solar power can be incorporated into remote power systems at a rational investment and operational cost. A combined wind-diesel, solar PV–diesel with battery energy storage (BES) or any other appropriate hybrid configuration can be developed to cope with the intermittent and stochastic behaviour of renewable sources (Kaldellis 2007; Kanase-Patil et al. 2011; Kempton 2010; Mondal & Denich 2010; Nema et al. 2009; Østergaard 2009; Roy et al. 2010; Rozakis et al. 1997; Zhou et al. 2010). On some remote islands micro hydro can be developed using surface rivers, but in the case of the Maldives integrating hydro is not an option; no surface water exists due to the low lying nature of these coral atoll islands. Renewable energy penetration has been reported as significant in some research (Armenakis 2010; Driesen & Belmans 2005; Lundsager & Bindner 1994; Mitra et al. 2008), and wind turbine systems are cost competitive compared to the photovoltaic's (Ashok 2007; Deshmukh & Deshmukh 2008b). The falling price of PV panels in the world markets would produce positive results for renewable systems. Greater penetration of renewable sources reduces the operational hours of the existing diesel internal combustion engines. This helps to further reduce air pollution. Significant quantities of water could be produced using desalination plants when excess energy is available. This is necessary because the fresh water layer on most of the islands in the Maldives has been depleted and on some islands the ground water is unusable due to its high salinity and bad odour (Clasen et al. 2006; Gadgil 1998; Gössling et al. 2011; Larsen et al. 2008; Sampat 2000; Zubair et al. 2011). There are some islands that have to use significant amounts of desalinated water due to bad water quality. This problem got worse after the 2004 Boxing Day tsunami. Consequently, the hybrid systems could efficiently fulfil the electrical energy and clean water requirements of numerous remote communities.

Remote areas supporting relatively small communities generally show significant variation between their peak loads and their minimum loads (Kanase-Patil et al. 2011; Nayar 2008; Phuangpornpitak & Kumar 2011). Diesel powered electric generators are typically sized to meet the peak demand but operate at very low loads during off-peak hours. Integrating renewable energy sources to save diesel fuel reduces the engine load further. This low load operation results in poor fuel efficiency and increased maintenance (Nayar 2008). Nayar proposes replacing the conventional diesel generators with doubly fed induction generators (DFIG) driven by variable speed diesel generators (in which the engine speed is adjusted to match the engine power output to the load power demand). These would be operating in the optimum fuel efficiency mode to overcome the problem of running at low capacity and this might give better results with intermittent renewable sources. The actual results of using renewable generators have not been included in Nayar's study as the research is ongoing, but the simulation results with renewable resources have been positive. The major benefits of using these variable generators would be the high penetration of renewable energy sources in remote diesel grid power stations without problems and that standalone diesel generators would perform more efficiently.

Integrating Diesel-Based Energy Systems with Wind and Solar Power

The most common and promising renewable energy sources that have been integrated into existing diesel generator sets are wind turbines and solar photovoltaic panels. So far these two sources remain the most promising of those available. Wind turbines and solar photovoltaic panels have been used to produce electricity for decades. Similarly, diesel engines have been producing electricity since the 1940s (Ackermann 2005; Borbely & Kreider 2001). However, the advent of the field of engineering concerned with the integration of wind and solar power into diesel generator networks only occurred two decades ago. In 1994 Ray Hunter and George Elliot published their landmark book, *Wind-diesel systems: a guide to the technology and its implementation*, in which they identified the concepts, as well as the major issues of the time (Hunter & Elliot 1994). The wind-diesel industry has grown exponentially since 1994 and is now in a large scale implementation phase (Baring-Gould et al. 2003; Ibrahim et al. 2011; Ibrahim et al. 2010; Kaldellis & Kavadias 2007). The technology behind each of the individual parts of hybrid energy systems (diesel-wind-PV) is mature enough to be used and it is being implemented in different parts of the world extensively. Hybrid systems with different combinations of resources are being implemented in both developed and developing countries.

This trend is most obvious when remote communities are implementing autonomous mini hybrid electricity systems; islands are one example of this. Hybrid energy systems are becoming technically reliable options for isolated communities in developed and developing countries. Beyond small communities, wind-diesel systems also have potential to be distributed in large utility grids in developing countries. Due to the large number of existing power systems worldwide that are based on diesel engines, the market for integrating wind and PV into these systems is substantial. According to the World Bank, over two billion people live in areas not connected to utility lines (Hakimi & Moghaddas-Tafreshi 2009; Martinot et al. 2001; Reiche et al. 2000). The market for integrating diesel based power systems with wind and solar power will experience huge growth in the coming years. The following schematic (Figure 2.1) represents a basic hybrid energy system with diesel generators, wind turbines, solar photovoltaic panels and a battery bank using a bi-directional inverter. The power conversion device can charge the battery bank when excess energy is available from the engine-driven generator. It can also act as a DC/AC converter under normal operation. A detailed review of the different topologies of stand-alone renewable energy systems and their operational characteristics has been presented by Wichert.B (Wichert 1997). Integrating solar photovoltaics and wind turbines with diesel generators for remote and rural areas would assist in expanding the electricity access in these islands more sustainably. However, the energy system designs for current and future unconstrained growth of peak loads lead to large battery energy storage requirements and over-sized systems.

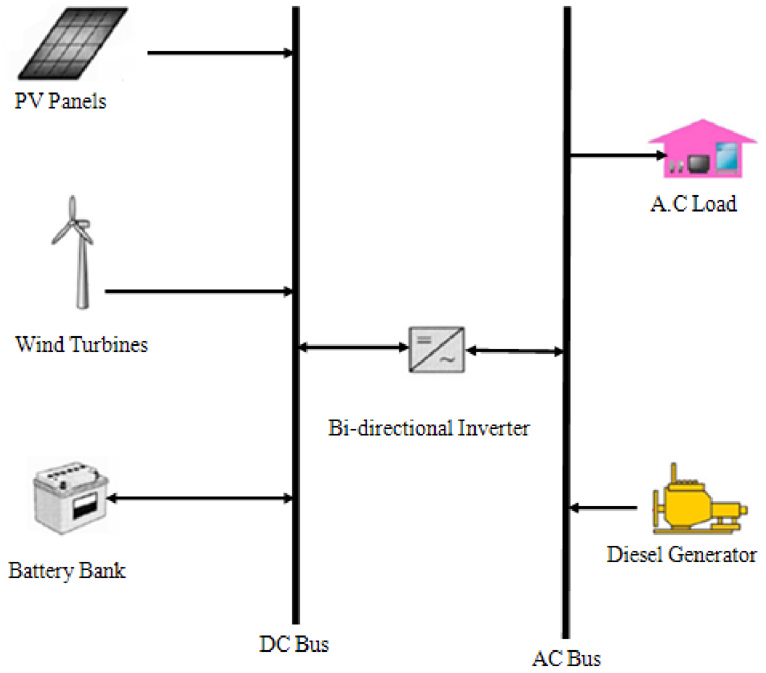


Figure 2. 1 Schematic of a hybrid energy system with diesel generators, wind turbines, solar photo voltaic and a battery bank. Source Nayar (Nayar 2008)

2.2 Sustainability Concepts

Sustainability is one of the core issues in energy engineering and is often discussed. Energy and climate change issues are at the core of most publications on sustainability. This section outlines sustainability definitions, concepts and frameworks, as well as popular sustainability indicators and indices; thus, the term and its evolution will be investigated.

Carew and Mitchell investigated how a group of Australian engineering academics described environmental, social and economic sustainability, and identified a broad range of actions that participating academics associated with achieving sustainability

(Carew & Mitchell 2008). The responses are varied, as can be seen in the excerpt reproduced below (Figure 2.2).

Box 1. Sustainability themes derived by workshop participants during 'Conceptions of Sustainability: Mapping The Territory' AaeE 2002 Professional Development Workshop

- *Holism and society* – Respecting and preserving community, cultural diversity, quality of life. Taking into account the societal setting and social implications of technological action. Being human centred.
- *Appropriate design* – Technology appropriate to the context. Serving social need, keep pace with social change. Affordable inventions. Using local resources and skills. Improves standards of living.
- *Changing the development paradigm* – Thinking about the future, globally. Systems focus. Alternative economic frameworks, redistribution of wealth. Recognising limits to consumption.
- *Responsibility and balance* – Taking responsibility for engineering impacts on environment and society, on a range of scales (e.g. local, global and temporal). Meets or balances human needs and wants.
- *Resource management/care* – Preferential use of renewable rather than non-renewable resources. Conservation of non-renewables. Recycling resources. Not using up the environment.
- *Safeguarding ecosystems* – Avoid/regenerate damage, foster thriving ecosystems. Sensitivity to all physical elements (e.g. air and water). Maintaining biodiversity. Consider non-human entities.
- *Participatory processes* – Ability to listen and appreciate a variety of viewpoints. Involve many disciplines, decision-makers, stakeholders in decision processes. Consult with the community.
- *Business imperative* – Coming up with affordable and/or profitable solutions. Wealth creation and wealth distribution. Economic payoff over the long-term.
- *Minimising impact* – Minimising or mitigating environmental impacts. Considering whole of lifecycle impacts. Protecting society and social diversity.
- *Philosophy* – Spiritual needs. Cradle-to-grave thinking. Considering the process and the task. Involving values. Engineering as serving or leading.
- *Integration* – The integration of social, environmental and economic systems.
- *Entropy* – We can only minimise impacts. The second law of thermodynamics makes sustainability impossible.

Figure 2. 2 Sustainability themes derived by Crew & Mitchell (Carew & Mitchell 2008)

The term *sustainability* is abstract in engineering terms. Logically, it means c*apable of being maintained over the long term* (Herremans & Reid 2002). Sustainability is often represented by three overlapping circles, which represent the social, economic and environmental dimensions of the concept as presented in Figure 2.3 (Sadler & Jacobs 1990). Fien and Trainer (Fien & Trainer 1993) and Hodge (Hodge 1997) have all elaborated on Sadler's original concept of sustainability. For example, an activity, process, region, or project is deemed sustainable if it maintains, supports, or carries the weight or burden of all three dimensions over the long term.

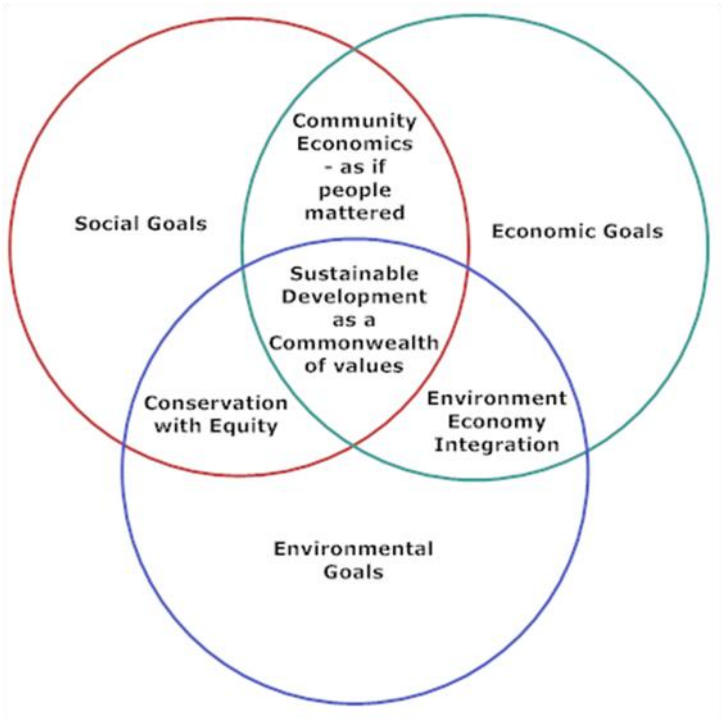


Figure 2. 3 A Systems Perspective on Sustainable Development. Source:(Sadler & Jacobs 1990)

The report "Our Common Future" published by World Commission on Environment and Development (WCED) describes important parts of the concept of sustainable development. This comprehensive report was produced through global partnership and constituted a major political turning point for the concept of sustainable development (Mebratu 1998). Since the publication of the Commission's report, sustainability has been used more and more in relation to human sustainability on Earth and this has resulted in the following widely used definition of sustainability and sustainable development:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

The above statement is probably the most broadly accepted definition of sustainability and was developed by the commission in 1987 (Brundtland & Khalid 1987). Often terms such as sustainable development, sustainable prosperity or sustainable genuine progress are used instead of sustainability. All of these terms are more or less defined as above.

The "Natural Step" is a non-profit organization founded in Sweden in 1989 by scientist Karl-Henrik Robèrt. It pioneered the "Back casting from Principles" approach as a way to effectively advance society towards sustainability (Holmberga & Robèrta ; Robert 2002). Their definition of sustainability includes four system conditions (scientific principles) that lead to a sustainable society. These conditions, which must be met in order to have a sustainable society, are:

Nature is **not** subject to systematically increasing

- concentrations of substances extracted from the Earth's crust
- concentrations of substances produced by society
- degradation by physical means.

People are **not** subject to

- conditions that systematically undermine their capacity to meet their needs.

2.2.1 Approaches and Methods

Meadows had written much about sustainability and is considered by some to be a pioneer in the field. The well-known model ‘world’, designed to analyse the predicament of mankind, was developed by Meadows and his team while in collaboration with Jay Forrester, a pioneer in Systems Dynamics. “The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind” (Meadows et al. 1972) is a well-known book documenting the results found by Meadows et al., who had been commissioned by The Club of Rome to analyse the “world problematique” using the computer model “World3” (Turner 2008). The World3 model examined the interactions of five subsystems within the global economic system, namely: population, food production, industrial production, pollution, and consumption of non-renewable natural resources (Turner 2008). In this analysis the chosen time scale was from 1900 until 2100. Meadows explained that in order to prevent our society from collapse we must reach an equilibrium state, meaning there can be no exponential growth. He explained the many positive feedback loops related to modern societies’ environmental and social problems. Mathematically speaking, constraints to stop exponential growth are negative feedback loops that in turn can be enhanced by weakening positive feedback loops. Such constraints can be easily implemented in the software model (e.g. by setting the birth rate equal to the death rate). How to achieve those constraints in the real world is not covered in Meadows’ work.

In the "*Limits to Growth: The 30-Year Update"*, scenarios of possible developments through to 2100 have been included. Using computer models of population, food production, pollution and many other data, the authors demonstrate why the world is in a potentially dangerous situation (Meadows et al. 2004). The main issue is that humans have been steadily using up more of the Earth's resources without replenishing them. The publication of 'Limits to growth' can be seen as the starting point of the modern sustainability debate.

2.2.2 Sustainability Tools

Life Cycle Assessment

Life Cycle Assessment (LCA) is perhaps the most widespread and most universally accepted tool for sustainability analysis of materials and products. Life cycle energy analysis is of particular interest here and it is an approach where all energy inputs into a product are accounted for—direct energy inputs for manufacturing and energy inputs for its components, materials and services for the manufacturing processes (Guinée 2002; Heijungs 1994; Powell et al. 1997). Energy analysis was an earlier term used to describe this approach.

Ecological Foot Printing

The ecological footprint is a measure of human demand on the Earth's ecosystems. It compares human demand with the Earth's ecological capacity to regenerate resources for sustainability in terms of productive land and sea area. This assessment tells if we are using more resources than Earth can re-new. This is a well-known sustainability indicator tool for the evaluation of the ecological impact of human activities (Wackernagel & Rees 1996). The Ecological Footprint analysis estimates the amount of ecologically productive land, sea and other water mass area required to sustain a population or manufacture a product. Quantities accounted for are the use of energy, food, water, building material and other consumables.

Triple Bottom Line Accounting

The triple bottom line (abbreviated as TBL or 3BL) is also known as people, planet, profit or the three pillars. This term has been commonly used since late 1990s after the 1997 publication of the John Elkington's ‘Cannibals with Forks’ (Elkington 1997). “Sustainable business” is the new managerial paradigm that Elkington presents. The concept is not a new one, but previously was limited to environmental sustainability. Elkington sets out to enlarge the concept by presenting a broad picture of what a social responsibility agenda for business should entail. Business is sustainable when it lives up to the “triple bottom line” of economic prosperity, environmental quality and social justice. The three bottom lines are interrelated, interdependent, and partly in conflict (Jeurissen 2000). Advocates of the “triple bottom line” paradigm encourage managers to think in terms of social and environmental bottom lines in addition to the financial bottom line (Norman & MacDonald 2004). The Triple Bottom Line concept refers to ethical business practices and does not directly affect resource continuity.

Ten Necessary Steps for Sustainable Energy

In his famous paper ‘Ten Steps to a Sustainable Energy Future’ (Rechsteiner 2004), the Swiss member of Parliament Dr Rudolf Rechsteiner talks extensively on the energy issues of today and in the future and the following ten steps are mentioned as being necessary for sustainable energy:

1. Decreasing per capita energy consumption and carbon emissions and enhancing thermodynamic efficiency of energy usage by introducing pricing and regulatory changes.

2. Attaining diverse electricity from primary renewable energy sources; to do this it is crucial that operators of all renewable energy systems recover their sometimes high up-front investment costs and get guaranteed feed-in tariffs that cover their specific generation costs, with regressive tariffs over time.

3. Developing models in order to apply guaranteed feed-in tariffs for electricity imports enabling access to cheap primary resources. This would mutually benefit export and import countries.

4. Introducing massive long distance HVDC electrical power transmission schemes to create energy security and gain access to low cost production areas from renewable sources. This could promote multi-way networks with electrons moving back and forth at different times to balance local or regional supply and demand to replace a one way supply structure going from the power plant to the user.

5. Producing electrical power locally to an extent to protect essential life line services and for security reasons. Locally produced energy needs to be able to compete with cheap imports.

6. Setting up the price signals as related to real time tariffs, thus enabling economic management of energy flows and optimal use of the generating capacity. Modern information technology can be used to manage the demand side, and to reduce the gap between production and consumption of electricity in time. The need to store electricity for peak times would then be reduced, thus reducing overall costs.

7. Providing storage where necessary, as close to the point of use as possible.

8. This renewable energy system should be based on a market system within which energy is produced where it is cheapest and most available in terms of capacity and time. Hence, subsidies given for non renewable sources that do not cover the costs should be stopped. Greater emphasis needs to be placed on correct pricing and stronger power transmission systems than on subsidising nuclear energy or coal.

9. Zero emissions building technology is readily available. We should not forget the cheapest resource we have: energy efficiency. Stringent standards should be imposed on all energy-consuming products—standards analogous to electrical safety standards but aimed at wasteful use of energy.

10. Research should be focused on harvesting and distributing energy from renewable energy sources and creating systems for better energy storage and more efficient methods for converting biomass into liquid hydrocarbon energy carriers.

2.3 Imminent Petroleum Shortage

This section provides an overview of the literature on petroleum forecasting and peak oil. General options for mitigation are briefly discussed. It took less than 200 years to develop the fossil fuel society we are in. In a little over a century, petroleum has become the most widely traded commodity in the world. The petroleum system has reached its peak according to many prominent researchers, a peak from which decline is inevitable.

Many theories have been put forward regarding the quantity of petroleum in the ground and its practical availability. The most successful of these came from the US oil geologist Marion King Hubbert, who in 1956 predicted that US oil production would peak in 1970 and decline thereafter (Rechsteiner 2004). The “Hubbert Curve” illustrated in Figure 2.4 demonstrates empirical experience based on geology and statistics: the practical availability of a region’s oil reserves over time describes a bell-shaped curve, similar to the Gaussian (Normal) Curve. Large fields are discovered first, small ones later. Rudolf Rechsteiner states that after exploration and initial growth in output, production plateaus eventually decline to zero. Figure 2.5 shows how the oil market would change from a buyers market to a sellers market once the peak oil production is reached.

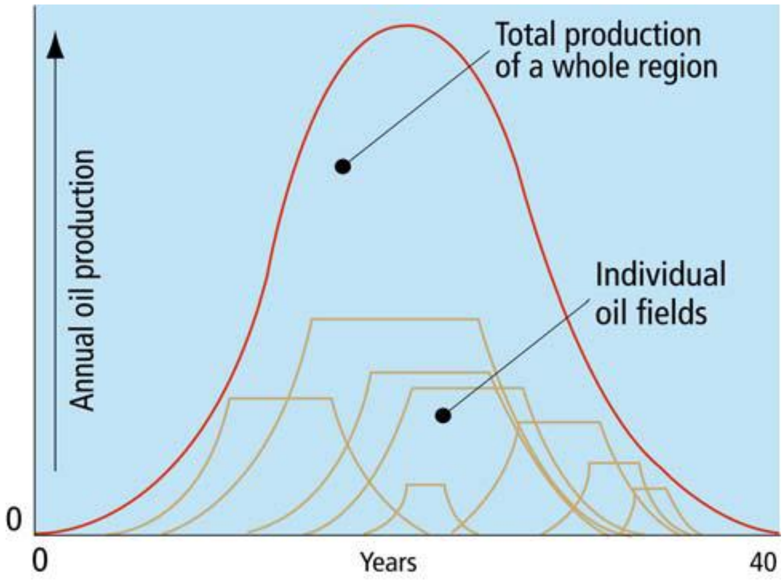


Figure 2. 4 Hubert curve (Source:(Rechsteiner 2004))

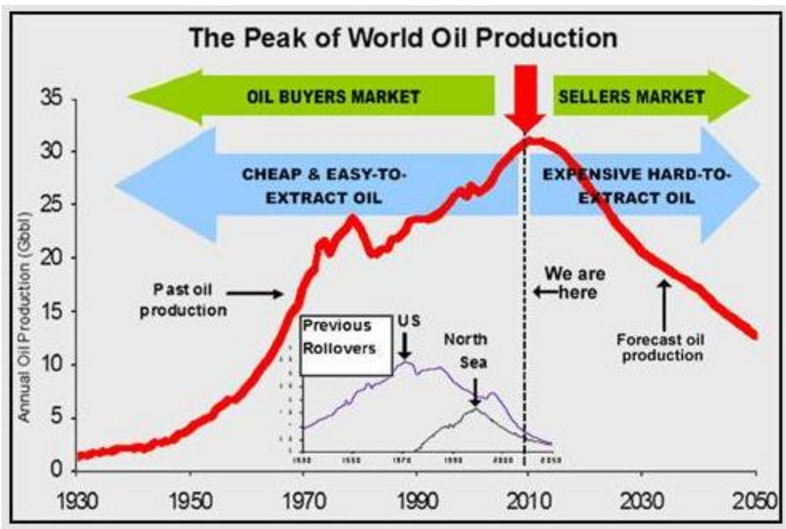


Figure 2. 5 Peak oil production of world. Source :(http://www.repowernz.co.nz/, 19.05.2010)

2.3.1 Petroleum Production Predictions

In 1956, Marion King Hubbert published his study on the lifetime production profile of typical oil companies, within which he accurately predicted a peak in American oil production to occur between 1966 and 1972 (Hubbert 1956); the actual peak occurred in 1971 (Bentley et al. 2007; Cavallo 2002; Duncan & Youngquist 1999). After Hubbert, many prominent petroleum geologists and other researchers published their own forecasts based on Hubbert's methodology. A representative sample of these predictions is shown in the Table 2.1.

Table 2. 1Global oil production peaking prediction dates

Global peak	*Forecaster*	*Background*
After 2007	(Skrebowski 2004)	Petroleum journal editor
2007 – 2009	(Simmons 2005)	Investment banker (U.S.)
Before 2009	(Deffeyes 2001b)	Petroleum geologist (ret. U.S.)
Before 2010	(Goodstein 2005)	Vice Provost., CalTech(U.S.)
Around 2010	(Campbell 2003)	Petroleum geologist(ret. Ireland)
Around 2015	(IEA 2008)	Internat. Energy Agency
2010-2020.	(Laherrère & Valery 2003)	Oil geologist (ret., France)
No visible peak	(Lomborg 2001; Lynch 2003)	Economists

2.3.2 Peak Oil Mitigation

Studies of the potential of renewable energy for providing the required energy services have been done by many different authors and researchers. It is now common practice for governments to undertake studies detailing the potential of renewable energy within their respective countries. An analysis of potential clean and non-polluting energy sources has been undertaken by Hoffert, Caldeira et al (Hoffert et al. 2002). This detailed analysis concludes that there exists no energy sources that can produce 100-300% of the present world power consumption without significant amounts of greenhouse emissions.

In the book "The Party's Over", Heinberg (Heinberg 2005) provides a broad discussion of existing (non renewable) fossil fuels and alternative (renewable) sources of energy, the oil production peak year for main oil producing countries and regions and how energy from both fossil fuels and renewable sources could be used. When analysing potential energy sources, Heinberg suggests using the following four main criteria:

Energy Returned on Energy Invested (EROI, EROEI) - is the ratio of the amount of usable energy acquired from a particular energy resource to the amount of energy expended to obtain that energy resource. When the EROI of a resource is equal to or lower than 1, that energy source becomes an 'energy sink', and can no longer be used as a primary source of energy.

$$EROI = \frac{Usable\ Acquired\ Energy}{Energy\ Expanded}$$

$$= \frac{Quantity\ of\ energy\ supplied}{Quantity\ of\ energy\ used\ in\ supply\ process}$$

Renewability - a renewable resource is replaced by natural processes at a rate comparable to its rate of consumption. A non renewable energy source with high EROI is of limited usefulness over time, as it will eventually run out. A sustainable energy source must be renewable and must have a significantly positive EROI.

Environmental Costliness – the extraction and use of all energy sources incurs some level of environmental cost; some sources pollute more than others. Even burning some renewable sources, such as wood, causes (air) pollution.

Transportability and Convenience – liquids are the easiest fuels to transport and use. The high energy density, easy transportability and relative abundance of oil have made it very convenient; oil has been the world’s leading source of energy since the mid-1950s.

Heinberg found that it will be physically impossible to fill the imminent difference between oil supply and demand with any combination of alternative resources. The view that our society will not be able to sustain today's power consumption beyond the global oil production peak is shared by Heinberg and some of the world’s most renowned oil geologists, such as Deffeyes, Campbell, Duncan and Youngquist (Campbell & Sivertsson 2003; Deffeyes 2001b; Duncan & Youngquist 1999). While literature on the possible implications of peak oil and imminent catastrophes is abundant (e.g. (Friedrichs ; Kunstler 2005)), suggestions as to possible mitigations are rare. Three different oil production scenarios were produced by Hirsch in 2005 (Hirsch 2005). These investigated options to mitigate the imminent risks posed by peak oil. Peak oil is riddled with various uncertainties, such as the year of peaking and also the immediate effects. Thus, peak oil is a typical risk management problem (Hirsch et al. 2006). Hirsch found that our options for successful mitigation strongly depend on the time period between the inception of mitigation crash programs and the date of peak oil. A significant supply shortfall could be avoided if mitigation programs started roughly twenty years before world oil peaking.

2.4 Renewable Energy for Electricity in Small Islands

As discussed previously, energy is intrinsically linked to the environmental, social and economic dimensions of sustainable development. Governments around the world have expressed considerable interest in renewable energy integration, as this helps reduce energy related environmental problems, particularly CO_2 emissions. There is policy support in several developing countries for funding more renewable energy research, particularly with regards to electricity generation. The main support is focused upon renewable sources such as wind energy and solar photovoltaic (PV) energy for electricity generation and biomass for heat. Wind turbine and photovoltaic technologies have made strong progress in the past decade, with substantial cost reductions and rapid market expansion. Other renewable technologies are far from commercial viability and require more development. The potential scale of renewable energy contribution is very large, but more policies are needed to make it more attractive and cheaper than convenient fossil alternatives. New technologies are being developed in this area fast, most notably the required power electronics that are considered to solve most of the system control problems in a near future. Hybrid systems are receiving widespread attention in recent research and are in the implementation stage throughout the world (Abdullah et al. 2010; Gross et al. 2003). The following are some examples of such projects.

The Wind/Hydrogen Demonstration System at Utsira Island in Norway

A demonstration energy system with autonomous wind/hydrogen energy located on the island of Utsira in Norway was officially launched by Norsk Hydro (now StatoilHydro) and Enercon in July 2004 (Ulleberg et al. 2010). The main components in the system are a 600kW wind turbine, a water electrolyser (10 Nm^3/h), hydrogen gas storage (2400 Nm^3, 200 bar), a hydrogen engine (55 kW), and a PEM fuel cell (10 kW). The system gives 2–3 days of full energy autonomy for 10 households on the island, and is the first of its kind in the world. The authors highlight the importance of improving the system’s efficiency in order to achieve a fully (100%) autonomous wind/hydrogen power system (Ulleberg et al. 2010). Utsira has a population of 220 and no local industry. A concept diagram is shown in Figure 2.6. This high technology energy system provides utility grade electricity to households. According to Norsk Hydro, the project cost is NOK40 million (www.Hydro.com) or US$6.5 million—an initial investment of US$630,000 per household. This kind of energy system will not be affordable or feasible at this cost for any developing island nation.

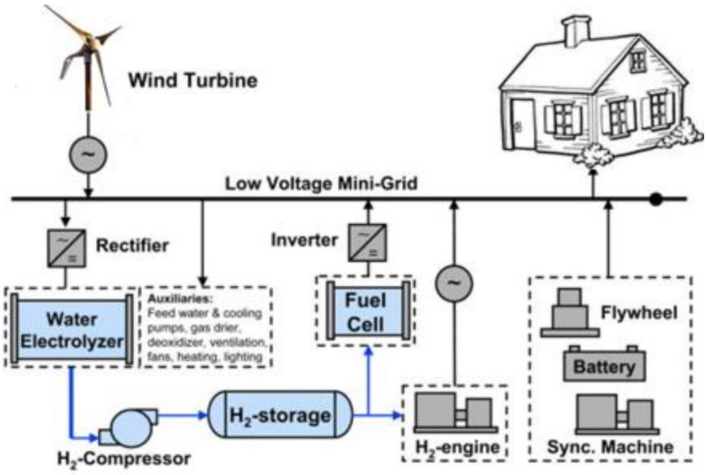


Figure 2.6 System schematic of the wind/hydrogen demonstration plant installed at Utsira (source:(Ulleberg et al. 2010)

Kythnos Island

The demonstration project on the Greek island Kythnos in the cluster of Cyclades in Aegean Sea is a standalone distributed generation system connected to 12 houses; it will be connected to the main grid in the near future. The islands' mini grid consists of a 10 kWp solar photovoltaic capacity distributed in five smaller sub systems, a battery bank of 53 kWh capacity, a diesel generator of 5 kVA nominal output power and three 4.5 kVA each battery inverters to form the single-phase grid. Each house has an energy meter with a 6A fuse as per the local electric utility. Special load controllers were installed at each house. The basic principle of the system layout is three bi-directional battery inverters, which form the AC bus with the help of the energy stored in the battery bank. Renewable energy-based AC electricity can be connected directly to this AC mini grid and the DC power from the PV modules is converted to AC power by solar string inverters. A detailed study of this system by Indradip Mitra (Mitra 2008) can be used to show its successful operation. Figure 2.7 shows the basic layout of the hybrid system.

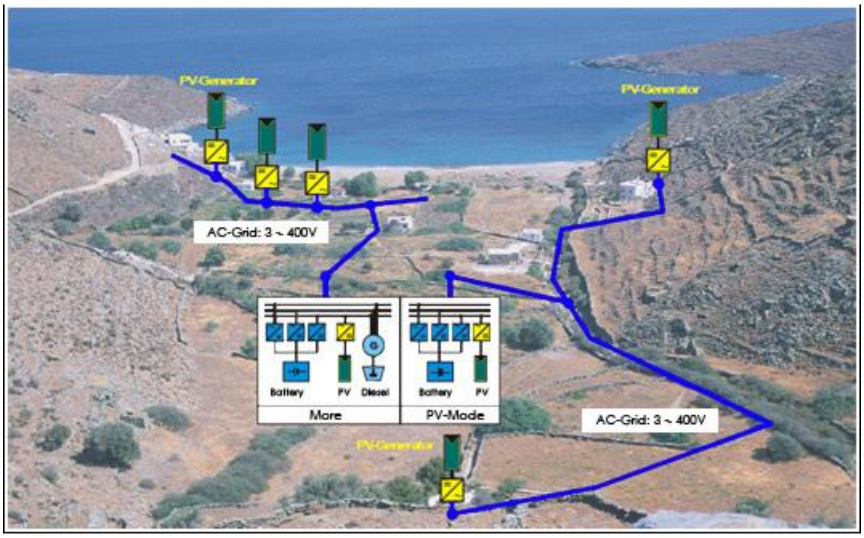


Figure 2.7 Project layout of Greek Kythnos Island – AC Hybrid system and AC PV system supplies to houses. Source: (Strauss et al.)

Hybrid Wind/Diesel Utility on Porto Santo Island

Porto Santo has 5,000 year long residents, with most living in the capital, Vila Baleira. This population increases significantly during the summer months. The number of tourists and part-time second house residents fluctuates between 500 in the wintertime and 13,000 in the summertime. The current grid capacity is mainly based on thermal units and a wind park with two 225 kW and one 660 kW Vestas wind turbines. It is planned to convert Porto Santo into Portugal's first renewable island, which would make it one of the 100 sustainable communities (100% renewable) in Europe; this project is currently underway (Duic et al. 2008).

Table 2. 2 Power generation system units in Porto Santo Island. Derived from (Duic & da Graça Carvalho 2004)

Generator type	**Capacity**
Thermal – Diesel	2 *3.5 MW
Thermal – Heavy fuel-oil	2*3.4 MW
Vestas wind turbine	2*225 kW
Vestas wind turbine	660 kW
Thermal – Heavy fuel-oil	4.1 MW

The existing wind-diesel hybrid system is summarized in Table 2.2. The modular nature of this system allows for 100% load coverage for the fluctuating demand on Porto Santo Island.

Samsoe (Samsø) Renewable Energy Island

Samsoe is a 112 km^2 island off the east coast of Denmark's Jutland peninsula. Home to 4,300 residents, the island is unique in the annals of renewable energy because it was the first to declare its intent to rely on renewable energy for 100% of its needs. The island’s proposal won a Danish government competition for communities that wanted to prove that they could live entirely off renewable energy. Within ten years, they became a 100% renewable island. Without any direct subsidy from the Danish government, the islanders built a 50 million Euro energy system. 80% of the capital for this was raised by local investors. During the brief summer months residents depend on the 50,000 visitors to the island. Traditional year-round occupations, such as fishing, have been in steady decline. The move towards becoming renewable was considered essential for the survival of the island. The island and its year-round residents needed a new strategy.

The island provides 70% of its heat with district heating plants. Gradually, islanders are increasing their use of biodiesel for liquid fuels. The islanders installed 15 new wind turbines to provide electricity. The turbines on land are owned individually by local farmers. To compensate for the liquid fuels used in transportation, the islanders installed ten 2.3 MW wind turbines offshore. Of these, two are cooperatively owned by 450 shareholders. Nearly everyone on the island has some interest in the island's wind turbines.

2.5 Common Software Tools in Energy Modelling

There exists numerous tools for energy modelling and analysis, but only the most widely used (based on number of downloads and sales) tools are considered here. A review paper by D. Connolly, H. Lund, B.V. Mathiesen and M. Leahy (Connolly et al. 2010) helped identify a suitable energy tool for analysing the integration of renewable energy into various energy-systems under different objectives. There is no one single energy tool that addresses all the issues related to integrating renewable energy; instead the 'ideal' energy tool is highly dependent on the specific objectives that must be fulfilled (Connolly et al. 2010). The typical applications for the tools considered range from analysing single households to analysing national energy systems. Many factors, such as the energy-sectors considered, the technologies accounted for, the time parameters used, tool availability and data from previous studies, will effect the choice of the ‘ideal’ energy tool. Commonly used software tools ideal for decentralised energy systems modelling and analysis include: RETScreen, HOMER, LEAP, energyPRO, EnergyPLAN, Invert and MARKAL/TIMES. Detailed descriptions of these seven tools are included in Appendix- E.

2.6 Possible Problems in Integrating Renewable Sources

A method for sizing and placing of distributed electricity generation (DES) systems in an electric transmission network has been developed and successfully validated by Niemi and Lund (Niemi & Lund 2010). Overvoltage situations are investigated, which is critical to the whole electricity system. The voltage drop increases as the distance increases from the generation point or from distribution box to distribution box; distribution boxes are being used on most of the islands in the Maldives. For future integration of renewable sources into the existing network and to avoid significant voltage fluctuations in the distributed generation system, using transformers would have many benefits in terms of power quality.

System integration issues and the mini grid operation will be central to accessing renewable energy sources. The power quality of decentralized systems that have a high proportion of renewable energy within small-scale electricity systems makes it challenging to operate the electric grid. Known problems include induced harmonics, voltage flicker, system reliability and voltage fluctuation due to large amounts of DES (Ackermann et al. 2001; Ha & Isaksen 1979; Hadjsaid et al. 1999; Tao et al. 2003; Zhiqun et al. 2004). One of the most critical parameters limiting the massive introduction of distributed energy generation in an already existing network is indeed the possible overvoltage that arises when supply exceeds consumption (Niemi & Lund 2010). Voltage issues are therefore of the utmost importance, as these are a potential source of physical damage and could restrict large scale DES penetration.

There have been many studies done on the issue of voltage and decentralised power generation in the past (Barker et al. 2000; Dugan & Rizy 1984; Jenkins 1995). The emphasis of these was mainly on safety, control, losses and grid reliability issues, especially in fault situations. The overvoltage situations were looked at in connection with various technical problems, e.g. islanding or single-line-to-ground fault and how decentralized power could help the grid to maintain its functionality in these situations (Wasynczuk 1984). Detailed investigations of the voltage issue are often based on sophisticated numerical grid simulations (Paatero & Lund 2007). Voltage and power quality issues have been specifically discussed (Dugan et al. 1984; Lee et al. 1984; Rizy et al. 1985), but often in qualitative terms. The dynamic behaviour of electric system can be accessed through a point by point calculation over time. Basically a DES unit causes a disturbance in the voltage throughout the line. It is particularly important to keep the possible overvoltage created within the allowed limits. For example, in a 20 kV medium voltage distribution grid, the voltage tolerance is approximately ±2%. This could be achieved by limiting temporal DES production, re-positioning DES units through DSM measures or electrical storage (Niemi & Lund 2010).

2.7 Regional energy – environment – economy system

In this section the preliminary theoretical considerations applied in this work are discussed. Krumdiecks' model of the regional energy – environment – economy system has been used to show the interconnectedness of different components of a regional energy system and the importance of its successful implementation.

Understanding the concept of a sustainable society is essential in designing a sustainable energy system and a sustainable energy system is necessary for a sustainable society (Hamm 2007). A sustainable society recognizes that its economy must operate within the limits of nature (natural resources) and any significant inequality in the sharing of the Earth's resources among human populations is inherently unsustainable. The earth's ability to sustain life is threatened by the way we have been extracting and disposing of vast amounts of its resources. This behaviour threatens long term economic activities.

If a particular system has high level of social or environmental risk associated with it then it is more likely to be an unsustainable configuration in the long run. In his book "Collapse: How Societies Choose to Fail or Succeed" (Diamond 2006), Jared Diamond explains how previous societies collapsed. According to Diamond, there are eight factors that contributed to the collapse of past societies:

- Deforestation and habitat destruction
- Soil problems (erosion, soil fertility losses)
- Water management problems

- Overhunting
- Overfishing
- Effects of introduced species on native species
- Overpopulation
- Increased per-capita impact of people

And, according to him, the four new factors that may contribute to the weakening and collapse of present and future societies are:

- Anthropogenic climate change
- Buildup of toxins in the environment
- Energy shortages
- Full human utilization of the Earth's photosynthetic capacity

Diamond found that society's response to environmental damage was the single most important feature of the failure of all societies that have failed. Two of the factors Diamond introduced can be subjected to risk analysis (to identify sustainable energy systems for these island communities). These are:

1. Energy shortages – Resource availability for the generation configuration considered.
2. Build-up of toxins in the environment – the fragile nature of these islands makes this of the utmost importance.

Krumdieck and Hamm (Krumdieck & Hamm 2009) argue that economics and behaviour are highly dependent and constrained by a peoples' prior experience of a built environment. They explain that un-sustainable behaviour is a problem of infrastructure and technology that cannot be entirely addressed by awareness or incentives alone. They propose that economics, engineering and science cannot independently fix the serious energy supply and environmental problems we are facing by simply focusing on component level projects such as extracting more renewable energy, efficiency improvements or consumer behaviour changes. A new, multidisciplinary, system-level approach is required to address sustainability issues in a successful way.

Krumdieck’s theoretical model of regional energy systems has been closely studied and applied in context while working on this project; where possible this project has tried to encompass the system level approach. The model is briefly discussed in the following sections.

2.7.1 Feedback Control Model of Regional Systems

An introduction to Krumdiecks’ theoretical model is supplied here as a reference; it has been applied to a number of publications (Krumdieck 2004; Krumdieck & Hamm 2009) in areas such as sustainability, continuity and feedback control.

For example, any graduate mechanical engineer understands that there is only one way to put together a compressor, heat exchangers and a throttle to make a heat pump. Operation of a thermodynamic system like a heat pump requires information, measurement and control at the systems-level. For example, the compressor, which increases refrigerant pressure, is not turned on in order to increase compressor consumption, but because a temperature measurement in the home was interpreted by a *controller to mean that heat was required. In engineering, we understand that systems are not simply a collection of components. ... Optimal system performance depends on coherent operation of components, not independent best interest of components. (Krumdieck 2007)*

Traditionally regional energy systems have been developed mainly from a component level perspective. This has only worked historically, as Krumdieck explains, because system capacities far exceeded demand. Krumdieck argues that a grossly overdesigned system can be reliable but does not make for an efficient use of resources. If available resources and environmental limits exhibit system constraints, efficient system designs require that these constraints be incorporated into the relationship between suppliers and consumers (Krumdieck 2007). Figure 2.8 is a representation of a feedback control system.

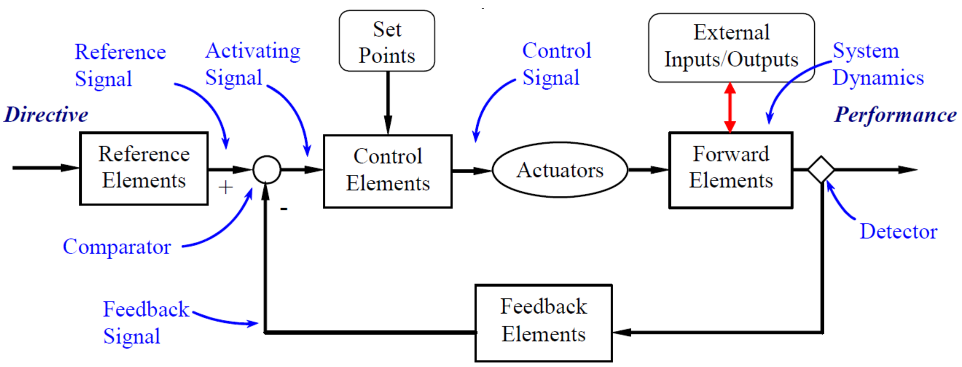


Figure 2. 8 The standard representation of a feedback control system, which is continuously controlled by the control elements so the performance achieves the directive. Figure taken with permission from (Krumdieck 2007)

2.7.2 Control Systems Theory Applied to Anthropogenic Systems

Control systems engineering aims to design systems with predictable behaviours. In engineering modelling, the analysis and control of dynamic engineering systems are accomplished through application of control system theory (Nagrath 2005; Palm 2000). Control systems maintain the stability of the designed operation and system. The system controls can only keep the physical system working as desired as long as the operational parameters of the system are not exceeded. How well a system responds to disturbances in individual element parameters and to feedback parameters is a measure of the robustness and reliability of the system (Krumdieck 2007). According to the control system theory, this is a fundamental representation of dynamic system behaviour that can be applied, in principle, to mechanical, electrical, biological and ecological systems. The basic form of a control system is illustrated in Figure 2.8. The system directive goal is represented by the input reference elements. The comparator determines the difference between reference and feedback and feeds this difference forward to the control elements. Control elements convert this into a control signal, which in turn causes physical changes to the system actuators. The actuators affect the performance of the forward elements, i.e. the physical plant. The performance is measured by detectors and feedback elements, which convert the detector signals to the same calibration as the reference signal.

If the cruise control of an automobile is used as an example, the directive would be a desired speed that is deemed safe and sustainable in the given circumstances at the given time. In this case, the system performance would be the actual speed. The controller would be a microprocessor, which passes control signals on to the actuators, i.e. fuel supply throttle and brake fluids. These affect the performance of the physical plant, which is the whole vehicle. Speed transducers detect the actual speed, and electronic calibrators (feedback elements) feed the signal back to the comparator. Krumdieck proposes "that the engineering and economics of sustainable anthropogenic systems can be understood by modelling the regional energy system as a feedback control system" (Krumdieck 2007).

2.7.3 Regional Energy Systems as Control Systems

The term "regional energy system" describes the energy supply and distribution infrastructure, the energy consuming devices, the people in a geographical region and the environment as both the providers of resources and the recipients of impacts (Krumdieck 2007). The theoretical model of Krumdieck's regional system is shown in Figure 2.9, and defines the system as any community of people and their relationships with each other through economic activities, the infrastructure that they use in these activities, including appliances, buildings, etc. within a given environment and resource setting. It is important to note that this is a model representation of the dynamics of the system. Changes in technology, the built environment or resources would change the system, and would therefore require an adaptation of the dynamic model to the new circumstances. With respect to Figure 2.9, the important terminologies used to describe the regional system are highlighted.

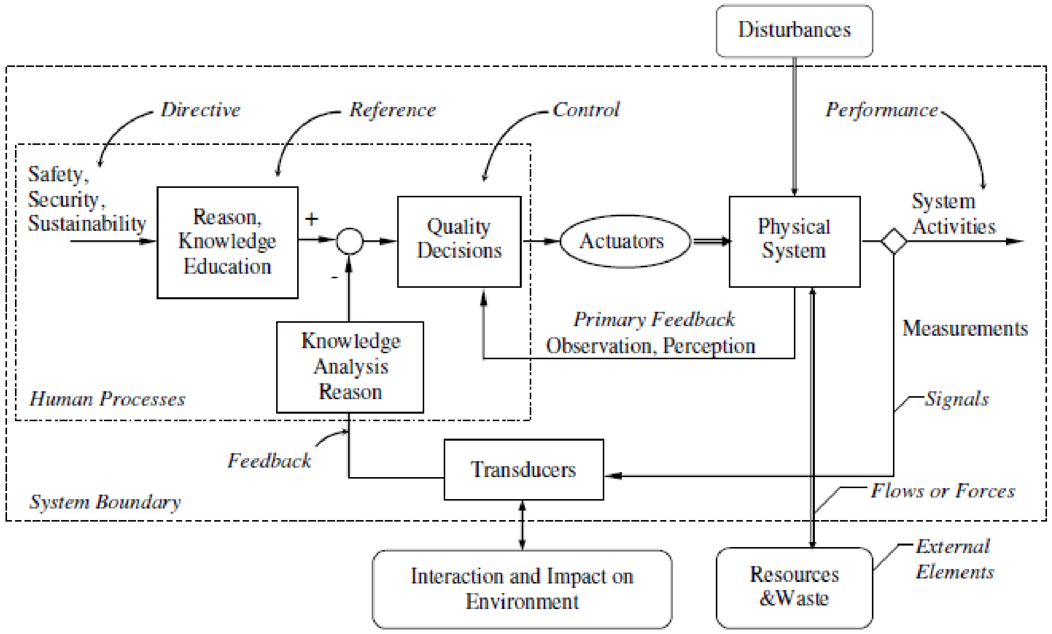


Figure 2. 9 The regional energy-environment-economy system model. Taken with permission from (Krumdieck 2007)

Directive – for a society this is a shared cultural vision and this vision depends strongly on cultural values, but is summed up best as people's desire to satisfy their various needs. If the regional energy system is safe, secure and environmentally sustainable, then it can continue indefinitely. The principal needs are the safety and security of the system with strong sustainability.

Reference Elements – these are represented by the levels of resource consumption and environmental impacts of a community carrying out their nominal activities using particular technologies but within sustainable resource limits.

The higher level directives are processed into the specific reference signal by means of knowledge, reason and education of the society. In other words, determining a *sustainable, safe and secure level of consumption, and impacts to support a certain level of activity would require a concept level system model for a specific region employing some specified set of technologies (Krumdieck 2007).*

Modern societies behave according to various social norms and rules that:

(1) Bank on future technological fixes;

(2) Use narrow indicators of welfare;

(3) Employ world views that alienate people from their dependence on life-support ecosystems; and

(4) Assume that it is possible to find technical substitutes for the loss of ecosystems and the services they generate (Pace & Groffmann 1998).

As Krumdieck writes, ancient societies usually had established reference signals allowing them to understand their relationships with natural systems. This dynamic knowledge had been developed and adapted throughout human generations through observations, mistakes and experiments. The single most influential factor in a society's failure or success was their reaction to environmental problems (Diamond 2005). For different societies the mechanism worked differently.

Feedback Elements: Under normal circumstances, a control system has several different feedback signals. In the model, Krumdieck refers to the two main feedback signals as primary and general. People make use of primary feedback directly and continuously to function effectively. As the main source of information for system control, the primary feedback (such as the knowledge of prices in different supermarkets for common goods) is directly observable. The general feedback includes information about the aggregate impact of activities on the environment, something that is not directly observable by individuals but by special observers and experts in the field.

Comparator: This continuously evaluates the feedback of actual measured consumption and its impacts against the reference levels. It is easy to understand how this would have worked in traditional societies: the indigenous knowledge of how to carry out day to day activities in a sustainable way would have been a strong shared cultural vision; the impact of people's activities on local resources would have been observable and understandable to people who relied on those resources for survival.

Control Elements: If the system is not performing according to the reference, then the controller determines changes in operation or forward elements. The controller in this model is an aggregate of day to day decisions by individuals. Decisions are made to maximize quality within the context of culture and the available built environment.

Actuating Elements: These are represented by the population's demographic composition in terms of economic status and lifestyle. When a decision is made that more heat is required in colder climates and more cooling in warmer places, people access these facilities through the economy. Krumdieck writes:

Popular opinion might be that cost drives people's decisions about consumption. However, the control system model indicates that economic relationships are actuators that determine how people access the goods and services they decide to purchase to *meet their needs and quality desires, not the reason they have desires or participate in activities. There may someday be information about the resources being used to provide the electricity, and people may develop a reference vision of minimizing evening peak loads to maintain secure supply and eliminate the demand for fossil fuelled generation* (Krumdieck 2007).

Forward Elements: This refers to the physical systems such as generation technology, transmission circuits, appliances and the built environment that the community uses in the course of going about their normal activities.

Flows across the system boundary: these are the material inputs to the built environment and the wastes emitted into the natural environment.

Disturbances: these physically change the built environment—construction and technological changes are good examples. While we normally think of the engineering of new technology and infrastructure as development, it is in fact a disturbance to a previously existing system. Control system theory refers to externalities such as material inputs and outputs to the physical system as “given” or “assumed available”.

This thesis aims to use Krumdieck’s energy system dynamic theory in an analytical and predictive tool that informs the design of a sustainable energy system. There is currently no developed method for a quantitative sustainability assessment of regional energy systems akin to the methods developed to assess the safety risks of appliances and the security of the electric supply systems. Krumdieck proposes that engineering practice to change the built environment to function sustainably is the primary requirement for sustainability. Nearly unlimited variations of human built environments have manifested themselves over time, all of which have had behaviours and economies that were rational in their context. It is not rational to behave in ways that do not fit the built environment or the economy of a given built environment. For example, "living off the land" in Manhattan would be dysfunctional, but foraging and living under canvas 400 years earlier in the same place would have been the only option. Krumdieck argues that behaviour and economy are much more determined by the built environment than the other way around. Thus, the engineering objectives for energy systems are that they be robust and affordable; they are also expected to operate in a renewable way with integrated education and communication to end-users (regarding demand behaviour) that is aligned with system stability.

Chapter 3

Sustainable Energy System Design Method

3.1 Energy Constraints and Adaptability

In this project a new methodology is developed for the development of a sustainable regional electric power system, which is then applied to a remote island situation. The system's ability to adapt to an energy constraint without negatively impacting the well-being of the people within it is a major design consideration. Essential energy end uses have been identified through energy audits and surveys. The electric power system is designed so that renewable energy sources alone can meet that "essential" demand with a plant that is both economically and technically feasible. One of the objectives is to design a system that is generally competitive with the present conventional power generation. The system's economic feasibility and risks to its capacity to meet the electric demand are analysed.

The method proposed in this thesis is based on finding the society's level of energy adaptability under constraints. This method should be particularly suitable for handling the complexities of a modern-day energy system in terms of planning a sizable sustainable energy and electricity system, either based on wholly sustainable sources or integrating sustainable sources of energy into a conventional generation system. Like most other systems these systems are also subjected to several uncertainties.

The term *energy constraint* in this thesis mainly refers to electrical energy supply shortages relative to the present levels. The level of energy constraint is determined using fossil fuel supply reduction as a reference, and *adaptability* is defined as how much of the present electrical energy could be cut without the cut having significant negative impacts on the wellbeing of the people living in the community. Two levels of constraint are explored in this work—moderate and severe. These are mainly due to the future decline of available fossil fuels and the expected high cost of diesel fuel, which is the only fuel being used in present generation systems. Possible changes in the use of electrical appliances are identified. The purpose of this identification of minimum electrical energy for essential services is to find the possible electrical energy sources that can supply the demand sustainably from a single or a combination of renewable energy sources. The literature review presented earlier in

Chapter 1 and Chapter 2 indicated that this is the first time this concept has been applied.

Sustainable Energy System

In this research, a sustainable energy system is a system that provides continuity of supply for electrical appliances that are considered by the residents to be essential and for which adaptability and resilience of behaviour were key design priorities over growth. The sustainable electrical energy supply should match the critical (essential) load and should have the ability to continue without major disruptions to the daily lives of the people in these communities. The term sustainability can be used in various contexts, as was discussed in the previous chapter. It is also a common assumption that renewable energy resources can easily be substituted for fossil fuels; this ignores the system as a whole and the changes in the built environment and end use demand that would be required.

3.2 Sustainable System Design Methodology

The brief introduction to Krumdieck's theoretical model of regional energy systems emphasised the importance of considering the systems level approach for successful implementation of sustainable energy project design. The function of this new method is to identify possible options for sustainable electrical energy systems when there is a resource constraint of diesel fuel and a system that is not destructive (or a system with minimum impact) for the fragile environment of these islands. The method proposed here is based on identifying the various electrical loads that are being used and how essential each loads is. This allows the loads to be categorised into each of the following categories (a) Optional, (b) Necessary and (c) Essential. An overview of the method is shown in Figure 3.1. Detailed step by step explanation of the method is in Section 3.3. After categorizing all the loads, the utilisation timing pattern of the appliances in each of the three categories was identified.

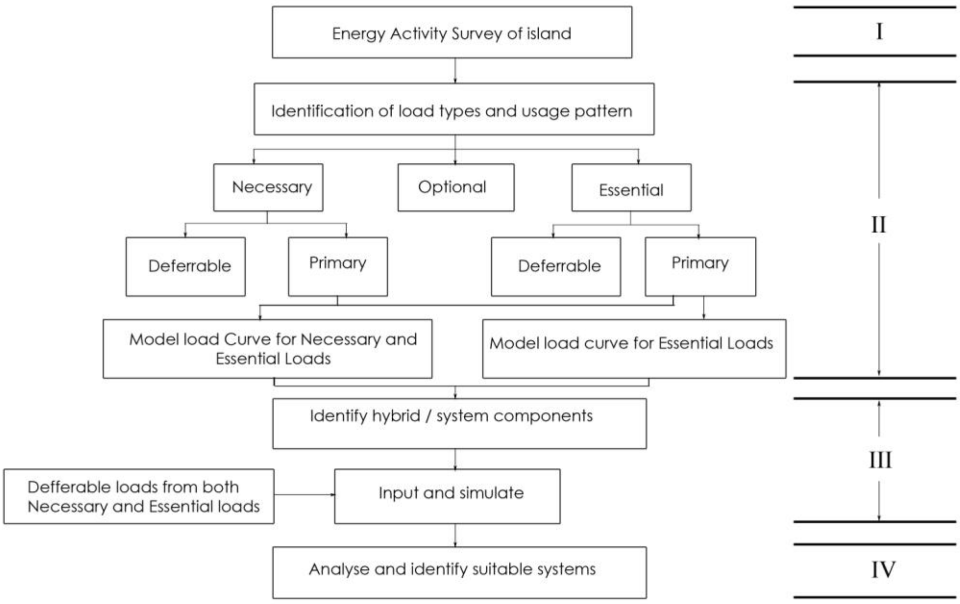


Figure 3. 1 Overview of sustainable energy design methodology developed in this research

Primary load refers to the electrical loads that must be met immediately in order to avoid unmet load. Deferrable loads are loads that must be supplied at some point during the day or week and that can be deferred if necessary. Primary and deferrable loads were separately treated to generate representative load curves for each category. Load categorisation as such makes it easier to quantify resiliency under constraints in fuel supply.

As illustrated in Figure 3.1, after generating the relevant load curves, the possible power generation system components are selected for simulation. In brief, the simulations generate thousands of possible system configurations depending on the number of sensitivities and components chosen. Through the application of economic and technical feasibility and risk analyses of resources and environmental impacts, the best possible system configuration will be chosen. The proper system design will be capable of meeting the essential load requirements with renewable energy and will be implemented in the future. From this methodology the minimum renewable energy to be integrated into the supply mix of the island electrical energy can be identified. The analysis will highlight the feasibility of the system, as well as the risks to it and its potential negative impacts. While it is traditionally assumed that consumption growth and economic growth are the ultimate objectives of an energy system, in the context of finding sustainable energy systems under fuel constraints, it is more useful to work towards providing energy services that people believe are essential for their wellbeing. A survey of energy resilience/adaptability should identify all the appliances and how people think those appliances fit into each of the three mentioned categories.

3.3 Steps Followed in the Methodology

3.3.1 Step 1 – Energy Audit, Renewable Energy and End Use Surveys

The first step is to carry out a detailed survey of the energy system. The main components of the survey include finding the energy usage pattern of the various appliances—noting the duration of usage and any available alternatives. The local availability of potential indigenous and non-indigenous energy resources on the island that could be used to replace fossil fuel generated energy is noted. Other areas surveyed are the present energy-service-and-supply system and its resiliency/adaptability in constrained situations.

The survey results should provide information on:

1. The existing energy system, including the services provided and the energy supply system,
2. Opportunities and limitations posed by the local environment and available resources,
3. The system's resiliency/adaptability under fuel constraints.

In order to understand the whole energy system, energy sources other than electricity have to be surveyed as well. On the electrical generation and supply side, data is collected on the system layout, system condition and system operation. The demand analysis is done by means of an assessment of the energy services supplied, and the use and importance of these services to the people. Possible outcomes include appliance penetration data, energy expenditures, energy use distributions and energy flow charts. All significant local energy resources are assessed in terms of available quantities and accessibility. The data gathered are inputted into the model.

A novel part of an otherwise fairly standard energy audit is the survey of resiliency/adaptability levels under various levels of electric power (or diesel fuel) supply constraints. This part adds a new dimension to traditional energy planning procedures that is necessary when designing sustainable energy systems.

3.3.2 Step 2 – Load Levels

This step describes how people's lives transform to accommodate a different set of adaptation levels and how this can be analysed with engineering methods. It is possible to generate individual electrical appliance load profiles. These profiles can be created from empirical data—appliance use profiles from regions with similar climates and similar energy service levels. In this study the profiles of appliance loads are generated based on the actual usage of the appliance. Appliance use profiles are used to generate the electrical load curves. For the two levels of energy constraint, namely moderate and severe, constraints in supply side have been studied and load profiles have been created for all households and other institutions. This provides the general load curve and the supply system is designed to meet that demand (load curve).

3.3.3 Step 3 - Energy System Configuration Simulations

Once reference load curves have been determined for each of the identified energy constraint levels, energy models are developed with different energy supply options. The available energy resources as identified during the surveys determine the energy supply options. Only commercially proven and technically feasible technologies are considered. System sizing and requirements, investments, life cycle costs and the costs of energy and emissions are computed separately for each option.

3.3.4 Step 4 – Feasibility of the System

Feasibility studies are performed on all energy system configurations, both in terms of monetary and technical viability, and the main areas of concern are identified. An issue is defined as a problem that needs to be resolved for successful implementation of the system. If no solution exists, the issue is taken as a risk to the system and all such risks add up to give the final system risk. System configurations with very high risks are not considered appropriate for supplying electricity. Risks arising from feasibility issues are quantified and included in the risk assessments. At this stage of identifying appropriate generation systems, two approaches are used: risk assessment of the generation systems and "a new approach to identifying the power supply system's suitability". These two approaches are used quantitatively in Chapter 7

Risk Assessment of the Generation Configurations

In Chapter 7, the risk assessment in the context of this study will be explored; this assessment will focus in particular on the various electricity supply scenarios (cases/options). Ranking scales are set to be used and defines the criteria that are employed when comparing the chosen energy supply system configurations. Some studies, such as that done by Hamm (Hamm 2007), have considered the effect of cultural dilution in traditional indigenous. This might not be relevant for this case study, as these islands already have unrestricted 24 hour electricity supply to domestic households and other institutions.

The risk assessment is qualitative in nature; the scales used are to be understood merely as guidelines. All risks (R) are expressed in terms of likelihood (p) and impact (i) as shown in Figure 3.2.

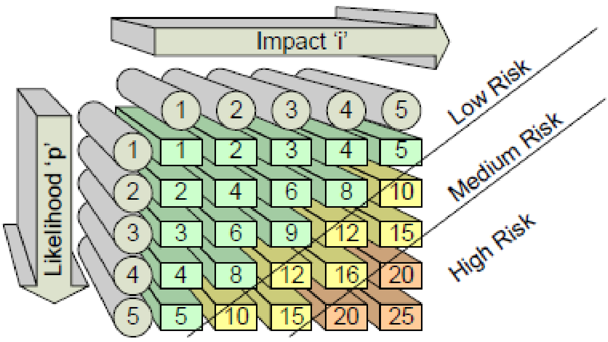


Figure 3. 2 Risk matrix, adapted from (Bedford & Cooke 2001; Vose 2008)

Energy Shortages or Resource Security

Since all the power generation of these islands currently relies on diesel fuel generators, the risk should be evaluated in association with declining conventional oil production. The probability is derived from the petroleum production forecast, while the impact is a measure of resiliency/adaptability under petroleum shortages and the final resource availability. From the current understanding of petroleum geology and recent advancements in mapping technology, there is a near 100% probability that global petroleum production will have peaked before 2020 (Campbell & Sivertsson 2003; Deffeyes 2001a; IEA 2008). Here it is assumed that fuel supply to a specific country will follow a similar trend to global fuel supply. Hirsch modelled three different scenarios of mitigation to the petroleum supply risk assuming 20 years, 10 years and 0 years of preparation time for a strategic risk management program. In this work the assumption taken is that there will be no preparation time, and that mitigation starts only after oil peaks. This assumption holds even if oil peaks sooner than this, as many prominent researchers have predicted. There are proposed methods for calculating the probability of peak oil occurrence in any given year. One such method has been demonstrated by Krumdieck, Page et al. (Krumdieck et al. 2010). The global energy supply scenario (Hirsch et al. 2005) is shown in Figure 3.3.

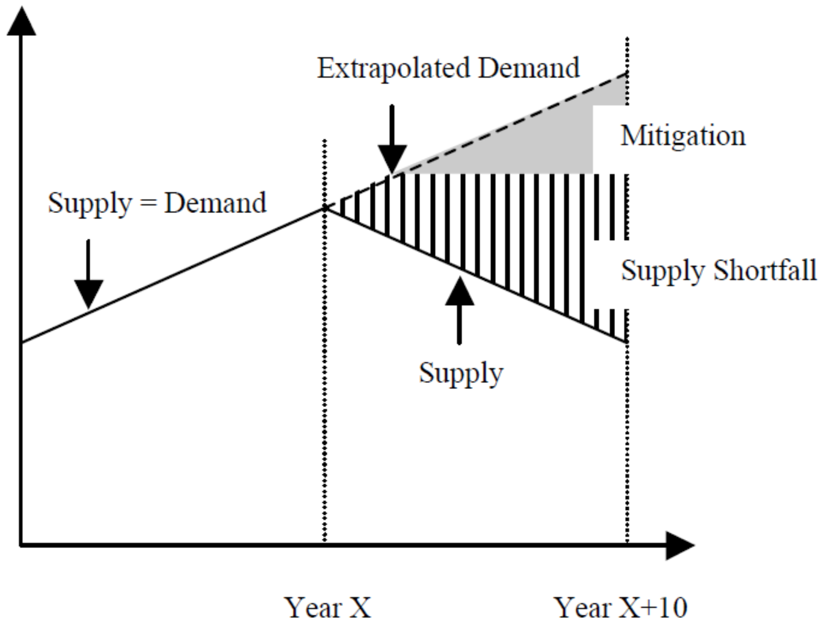


Figure 3. 3 Modelling future fuel supply shortfall (Hirsch 2005)

In addition to the risk of petroleum supply shortages, risks of other resource shortages (such as the supply of photovoltaic panels due to material shortages and wind turbines) could be considered, depending on the resources associated with the proposed system configuration and the status of the materials concerned in the world market.

In summary

In this research, a sustainable energy system configuration is defined as a system with the capability of continuity under identified, constrained fuel supply issues and risks. The system should be able to provide the required critical load in constrained conventional fuel supply situations within the adaptability range. The major priority in choosing supply system components is creating a design that will not be interrupted by various forms of global and local fuel crises and complies to all risk elements outlined in Chapter 7. It is therefore of the utmost important to mitigate the risks to the energy supply system. The mitigation of this risk is likely to involve much more than replacing fossil fuels with renewable energies; hence this approach expands the scope of analysis to include various levels of energy constraints when determining the appropriate minimum service levels.

Chapter 4

Energy Survey

4.1 Introduction

This chapter presents the results of an energy survey carried out during the field work in 2008. The results focus on the island's electricity production and how electricity is accessed by households, industrial-commercial and government institutions. The entities surveyed are summarized in Table 4.1 and the survey results are documented in subsequent sections of this chapter. A brief description of the status of the capital's power generation is included in Appendix H.

4.2 Survey Methodology

4.2.1 Domestic Energy Surveys

In carrying out the domestic energy survey, the general methods for formulating a survey questionnaire were adapted from the "surveys in social research" by (De Vaus 2002) and steps from Hyman (Hyman 1983). General energy auditing methodologies were followed when carrying out the survey (Turner & Doty 2006), which included the Australia/New-Zealand energy audit code 2000. The domestic energy survey focuses on domestic electrical appliances, but also includes energy use for cooking. The thermal envelope was not considered because there was no domestic air conditioning on the island at the time of survey except for two units of 9000 BTU that were installed and commissioned at the end of the survey period at the island health post (health centre).

Note: An Audit survey accounts all electrical appliances and any other energy use of the household, where as adaptive survey collects information about the levels of adaptability in energy use in constraint situations. Power house is referred to the building where the generators and its control systems are housed.

Table 4. 1 List of items surveyed

Entities	**Survey activities**
Domestic	-100 audit surveys (electrical appliances and other energy sources) -33 adaptive surveys
Powerhouse	Load curve, control panels, fuel
Public institutions	Island office, School, Health centre, Pharmacy, Mosque, Court (judiciary)
Commercial	8 grocery shops, 6 tourist shops, 2 cafes
Industrial	2 carpentry workshops, 2 boat-building sites

It is uncommon for researchers to survey an entire population for two reasons (especially when dealing with a large population): the cost is too high and the population is dynamic, with the individuals who make up the population changing over time. For this reason researchers often survey a representative sample of the population. The main advantages of sampling this way are that costs are lower, data collection is faster.

The domestic survey has two parts. Collecting information about the electrical appliances (such as the power rating and number of appliances) is the first, while the second involves investigating how much these appliances are used, how essential they are, their impact on wellbeing and the availability of alternatives. The first part of the questionnaire concerned all the households on the island, while the second part only dealt with 33 households. This is because the second part takes a long time and involves a lot more discussions with individual residents.

Adaptive Survey

The second part of the questionnaire is to ascertain each resident's level of resiliency in situations where energy constraints exist. The objective of this survey was:

- To find out how flexible the residents were in their usage of mainly electrical appliances and how essential they feel different appliances are.
- To find out if there were any alternative ways of getting each service in a situation where conventional fuel supply was constrained—with a particular focus on the services considered essential by the residents.
- To find out how many residents consider particular appliances essential.

The residents were asked to classify each of the appliances in their household on a scale of 1 to 10 of importance in their daily life, or to say if they considered the appliance to be optional, necessary or essential for their well-being.

This island survey did not pose particular challenges to the surveyor, as the surveyor was born in the Maldives and had grown up there and thus was familiar with the traditions, language and practices of the residents. Most of the information on its energy system and energy use was also familiar. Knowing about the culture, people's attitudes and other sensitive issues made conducting the survey and getting the right information easier. Prior to the field visit survey forms were approved by the University of Canterbury Human Ethics Committee. The survey was predominantly carried out in the form of informal interviews at the residents' homes. The author did all the interviews personally, but some locals helped with getting electrical and appliance information and information on the structure of some households. The original questionnaire was written in English, even though most of the interviewing was conducted in the local language "Dhivehi".

The questionnaire form used for this survey is shown in Figure 4.1 and Figure 4.2. For practical reasons, the chosen sampling method for the second part of the questionnaire was convenience sampling. As its name implies, convenience sampling refers to the collection of information from members of the population who are available and interested in participating and providing information. Compared to probability sampling (any method of sampling that utilizes some form of random selection), this method is theoretically inferior as systematic errors can occur (Fink 2008). For example, a particular category of households could have generally been unavailable during the times of day the survey was carried out. This was an issue in some cases and interviews had to be rescheduled; often they took place at night, during the evening or on weekends. Every household on the island was considered in the survey at some level.

Objectives of this Study

The aim of this questionnaire is to understand the energy (mainly electricity) usage pattern of typical island communities of the Maldives, their willingness and ability to adjust power consumption especially in an energy constraint situation. Assess energy saving possibilities due to household-orientation and building materials being used since a significant amount of cooling appliances are being used in these islands because of its geographical location (warm and humid throughout the year).

1. Year your house was built …………..
2. Number of people in your household ………..
3. Number of bedrooms/rooms in your house………
4. Number of living rooms in your house ………
5. How many stories above ground level are there? ……………
6. Which direction does the front of your house face? ………..
7. Is it possible for cross wind in your household? Yes / No.
   If yes, what is its orientation? ………
8. What type of foundation does your house have?
9. Which material is used for the roofing? …………..
10. How many windows are on each side of the house? ………
11. Does your house have a ceiling? ……..
12. What cooling appliances do you have?

13. What price do you pay for your electricity?
    View past bills if possible
14. Which form of energy do you use for cooking?
    Gas/firewood/electricity
15. What time does your day start? What are the first activities?
16. Which appliances are normally used and for how long?-
    Get details from audit sheet
17. Do you take any energy conservation measures?
    List in order of priority (electricity or others)
18. Are you concerned about the cost of your energy bills?

Very concerned									Not concerned
1	2	3	4	5	6	7	8	9	10

19. What is the maximum amount of money you are willing to spend on energy (electricity &gas)?
    For electricity
    For gas
20. If your electricity price were to go up, what percent increase above your last bill would you consider a large increase?
21. If the energy cost were to rise, how would you change your activities?
22. How many of your activities can be changed to other forms of energy? What alternative forms of energy could you use?

2

Figure 4.1 Questionnaire used to get detailed household and adaptive information

23. In an energy constraint situation what would be the first changes in your usage? Alternatively, what will be the first appliances that you will stop or reduce using?

24. Do you have any battery-powered appliances at your home? If yes what are they?

25. Do you have any device using any form of renewable energy?

26. How reliable is the power?

Very Reliable									Not Reliable
1	2	3	4	5	6	7	8	9	10

27. Do you think/believe that you could reduce your electricity/energy use without much impact on your standard of living? If yes by how much?

28. Do you believe there is any impact on the environment due to the electricity/ energy you use?

29. If there were an environmental problem, how willing would you be to take energy conservation measures?

Figure 4.2 Questionnaire used to get detailed household and adaptive information (continued)

Energy audit data sheet

Item No.	Equipment description	Name plate rating (BTU/hr,kW,hp,..)	Conversion factor to kW	Est. % load (100, 50,)	Est. hrs use per period	kWh	Conversion factor	Total energy use per period	Remarks/comments
	Home Entertainment								
	Colour TV								
	VCR/DVD								
	Radio/Cassette								
	Computer								
	Monitor								
	printer								
	Facsimile (Is. Off)								
	House wares								
	Sewing machine								
	Vacuum cleaner								
	Food Preparation								
	Refrigerator								
	Fridge								
	Freezer								
	Blender/Mixer								
	Microwave								
	Toaster								
	Rice cooker								
	Stove								
	Boiler								
	Sandwich maker								
	Laundry								
	Washing machine								
	Iron								
	Clothes dryer								
	Comfort Conditioning								
	Florescent/Energy saving Lights								
	Incandescent Lights								
	Fan(specify..attic or ceiling, circulating, roll away, window…)								
	Air conditioner								
	Health and beauty								
	Hair dryer								
	Shaver								

Aquarium oxygen filter, Electric insect repellent, water pump and motor,
Gas cooking, Firewood,
Past electricity bills

Figure 4. 3 Domestic energy audit questionnaire used in island energy auditing

Other Energy Surveys

Information on government institutions and businesses about the operation and services provided by these places is recorded in detail and generally enough data were obtained to perform a conclusive analysis regarding appliance use, cost analysis and potential energy saving options.

4.3 Island Energy System

Fenfushi's electrical energy system is a community owned diesel generators that provide electricity to the island. The island power house operates 24 hours a day to supply electricity to households and other entities such as government institutions. Electricity is used for all domestic tasks except for cooking. The main (most commonly used) domestic appliances include ceiling fans, lights, fridge-freezers, small individual household water pumps, televisions sets, radios, etc. In the following sections general household appliances and their average power range ratings are described.

Figure 4. 4 Google Arial view of the island of Fenfushi in the south Ari Atoll of the Maldives

Fenfushi is situated in the south west corner of the South Ari-Atoll. It lies about hundred kilometres from the capital of the Maldives. The island has a registered population of just less than eight hundred people, but the resident population was about six hundred at the time of survey. There were seventy eight households, with many plots cleared for housing. Many houses have been abandoned as the extended families move to live with their immediate family; as a result the parental house becomes temporarily vacant and many such houses are divided among siblings.

4.3.1 Electricity System

The island's electrical generation capacity consists of one 40 kW, two 60kW and one 160kW generator sets. However, there is no synchronisation mechanism to run generator sets simultaneously. At the time of the audit, only a 60 kW and the 160 kW generator sets were in working condition. Figure 4.5 shows the present set up of the diesel generators at the power house; (a) 160 kW, (b) 40 kW, (c) and (d) are each 60 kW. Figure 4.6 shows generator control panel indicators. Ownership of appliances has increased steadily since the commission of the first community-owned power house in the nineties. Prior to that electrical power was supplied by a private firm, beginning in the mid-eighties. Soon after the connection of the initial generator set, a second firm started providing electricity until the community bought both power houses and combined the two into a common supplier.

The powerhouse does not have a computer system for record keeping or accounting, or a proper manual mechanism to do so. The billing process is done manually, which may be appropriate given the number of consumers and the areas over which they are spread. There is a need to develop a comprehensive record of power station performance. This will allow technical and financial performance to be evaluated and longer-term projections made. To achieve this, it would be necessary to have the total generated energy, fuel consumption and other service and maintenance details entered daily into a simple spreadsheet and, where possible, to have historical performance determined from archived records of past operation. There is also a need to record specific events like the changes in tariffs that happened in early 2008. This increase of 400% in some sectors was due to the global fuel price increase and the addition of loads and outside supply arrangements to major industrial consumers such as the boat builders. The electricity bill comprises only the total energy consumed in kWh. At present, there is no consideration of the low power factor and this is unlikely to be considered in the near future. There has been no charge component based on time of use or The Time of Day (TOD) tariff; instead a flat rate of about US$0.4 per unit (kWh) is charged. Some islands have higher flat rates and some have rates based on different bands of usage.

Figure 4. 5 Diesel generators at the powerhouse; (a) and (d) are in working condition

Although the power house is owned by the community, the two newly installed generators were heavily subsidised by the government. In 2007/2008, the government contributed towards fuel purchase as diesel and other conventional fuel prices went up nearly 300%.

Figure 4. 6 Generator control panel showing important indicators

The generators are connected to several distribution boxes, which provide individual household connections. The grid is based on 35mm^2 3-wire underground cabling with a nominal voltage of 240V.

4.3.2 Present Load Pattern

As can be seen in Figure 4.7, there is a significant behaviour change in power usage during the month of Ramadan. The afternoon becomes a period of high consumption due to extra food preparation that utilises special electric ovens. Also people are active till late into the night during this period and sleep later in the morning, which is reflected in the respective load curve (Figure 4.7).

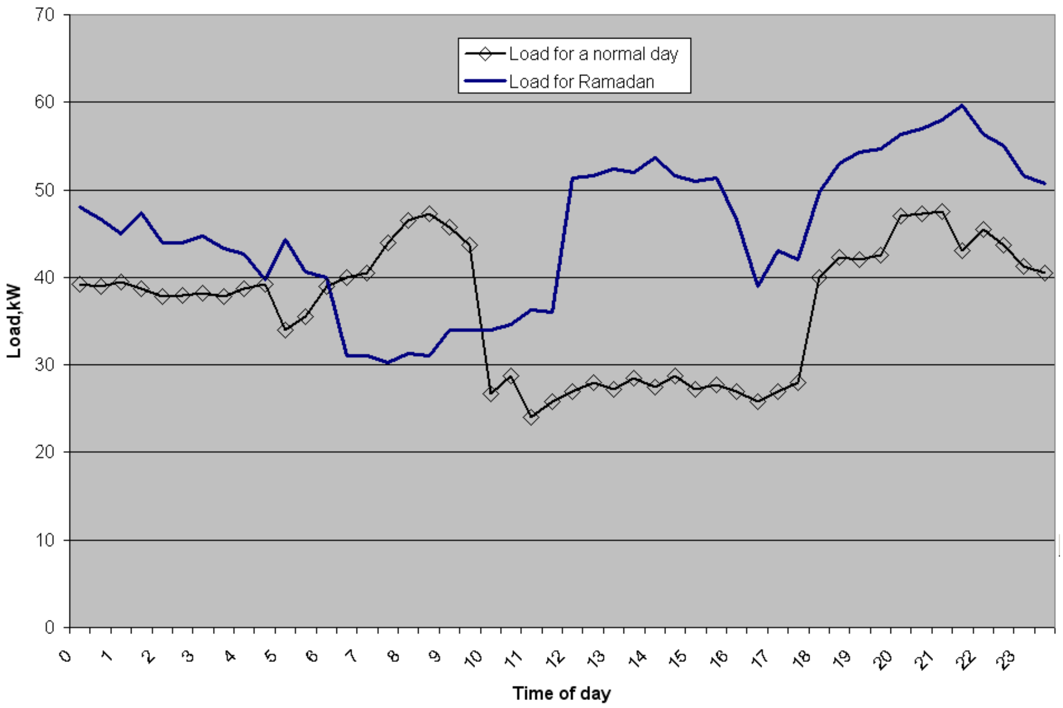


Figure 4. 7 Load curves of electricity generation for a normal day and a day of Ramadan.

The evening peak is mainly due to lighting, with about 4.6 kW contributed by street lighting. Along with domestic households, all other entities such as businesses and governmental institutions were served by the same community power house. The actual load curve is plotted using hourly data from the power house meters. The load curves for the moderately constrained and severely constrained cases were plotted using the hourly load generated from the survey data on the usage pattern of various electrical appliances, and summing up the loads of individual households and other entities of the community.

4.3.3 Electricity Use

Appliance ownership and average usage

This section describes the electricity services delivered throughout the island. Table 4.2 shows the level of appliance ownership and the average wattage used by most common electrical appliances. However, there are considerable variations between households with respect to the number and type of appliances and, most importantly, the usage pattern.

Table 4. 2 Electric appliance ownership and wattage range

Appliance	Average ownership level (Number per household)	Average power rating (W)
Electric fan	5	50- 85
Refrigeration	0.94	89 -150
Water pump	0.82	100 - 450
Lights	9.8	11- 20
Television sets	1.3	60 - 110
Clothes-washing machine	1.2	180 -450
Iron	1.2	900 - 1200
Microwave oven	0.39	800 - 1200
DVD player	1.3	15
Radio	1.1	18 - 50
Oven	0.8	500 - 1200
Blender (mixer)	0.91	550 - 600

Figure 4.8 shows the percentage of households that own a particular appliance. All households own electric fans, lights and an iron. Figure 4.9 shows the total power

used by the installed appliances and the amount of energy consumed by a randomly selected sample of 33 households. Figure 4.10 shows the total monthly electric energy used by different sectors, with between 75% and 79% of electricity consumption attributed to the residential sector.

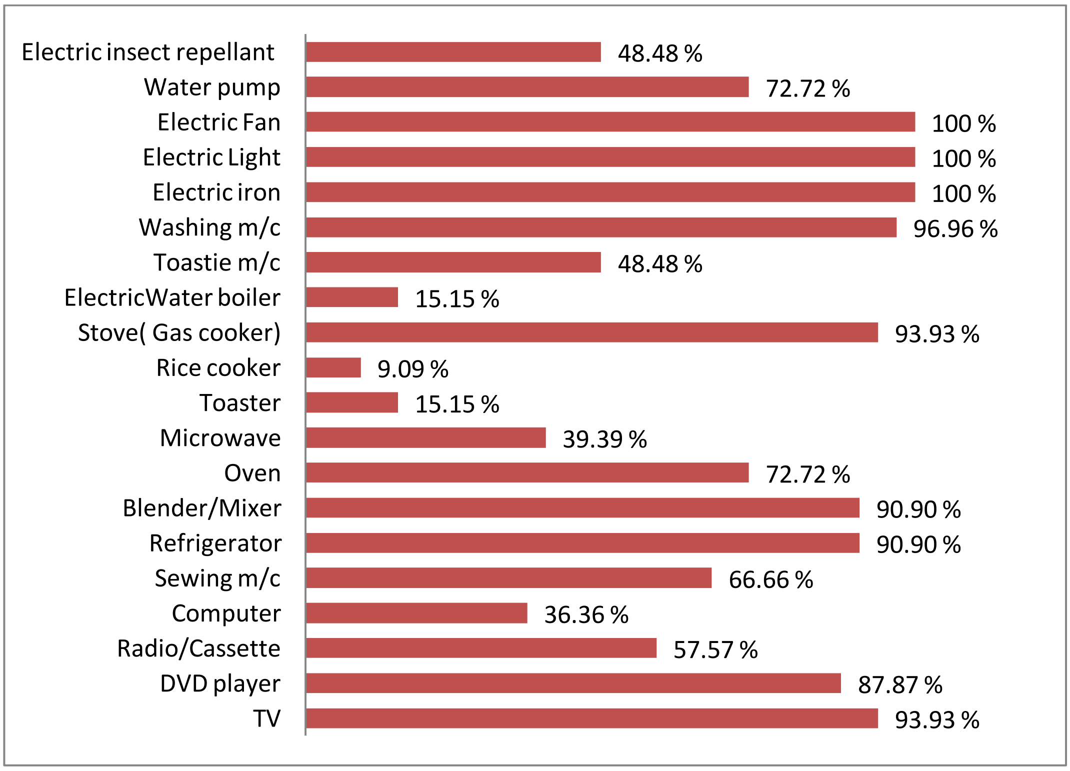


Figure 4. 8 Percentage of household appliance penetration

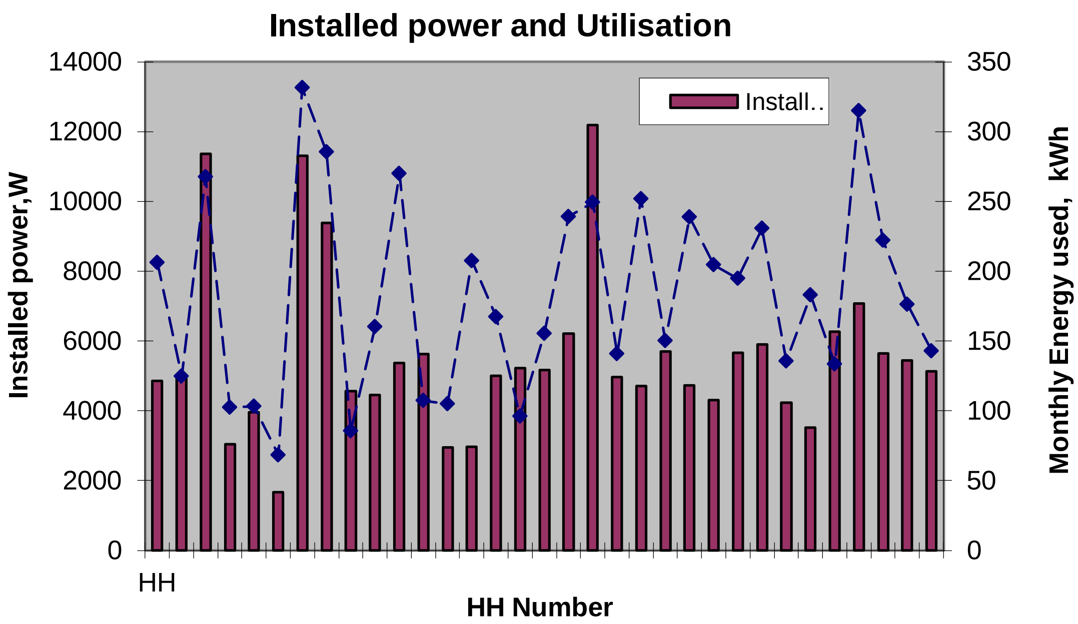


Figure 4. 9 Electrical energy consumption and total power installed for a sample of 33 households

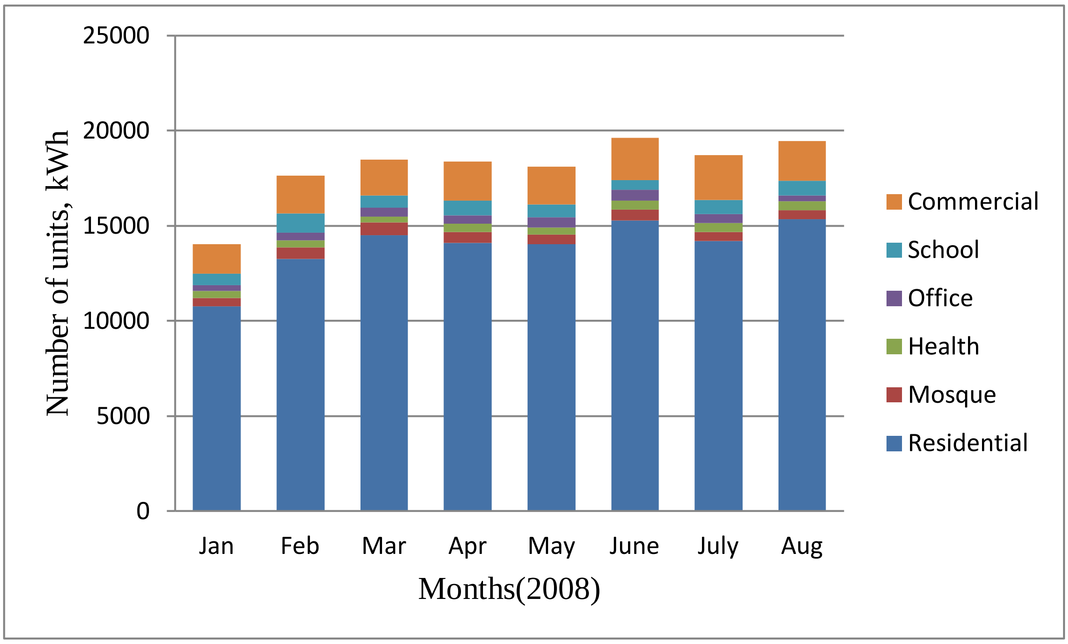


Figure 4. 10 Electric energy consumption by each sector from January to August 2008

4.4 Electric Power Usage under Constrained Scenarios

The following are some of the electric energy utilization patterns observed in the constrained scenarios. Under the constraints all households had a very similar pattern of electric power usage. Power consumption increases with the number of people and size of the household, with the number of fans and lights proportionally increasing with the number of rooms in the house. The main contribution is from the electric fans and lighting during the night. Most households have a small base load of 30 Watts from their fridge-freezers. On average 0.95 kWh and 0.42 kWh of deferrable loads are consumed per day under moderately and severely constrained scenarios, respectively. Figure 4.11 and Figure 4.12 show the percentage of household residents that consider each appliance essential or expendable in an electric energy constraint scenario. When asked about the first appliances that they would stop using in a constrained situation, 15% could not decide and replied “don’t know”. More than 60% of the households did not think electric water pumps were essential, because the ground water wells are shallow and they know they can easily use hand pumps, buckets or traditional “dhani” to get access to water. Figure 4.14 and Figure 4.15 show shallow water wells and traditional “dhani”.

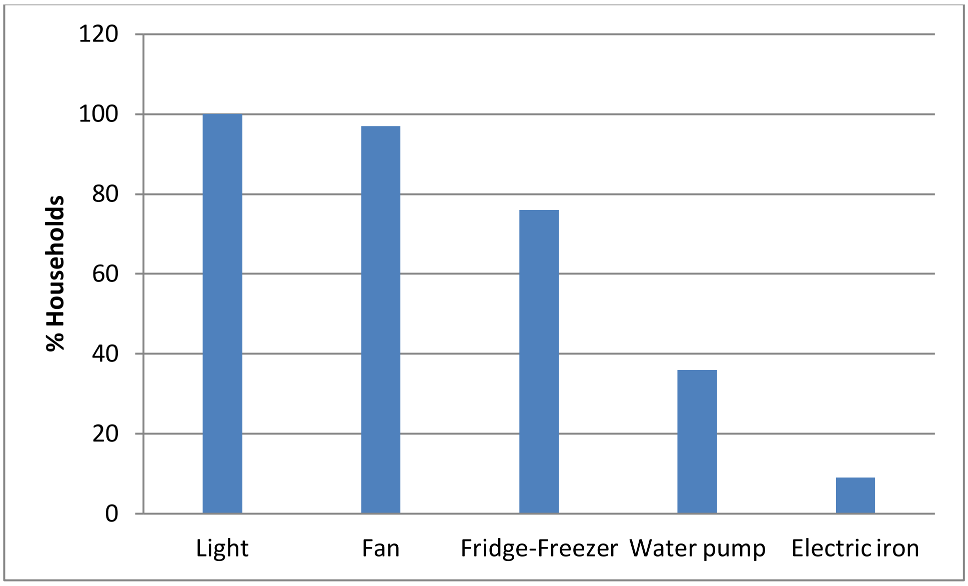


Figure 4. 11 Essential appliances considered by the residents

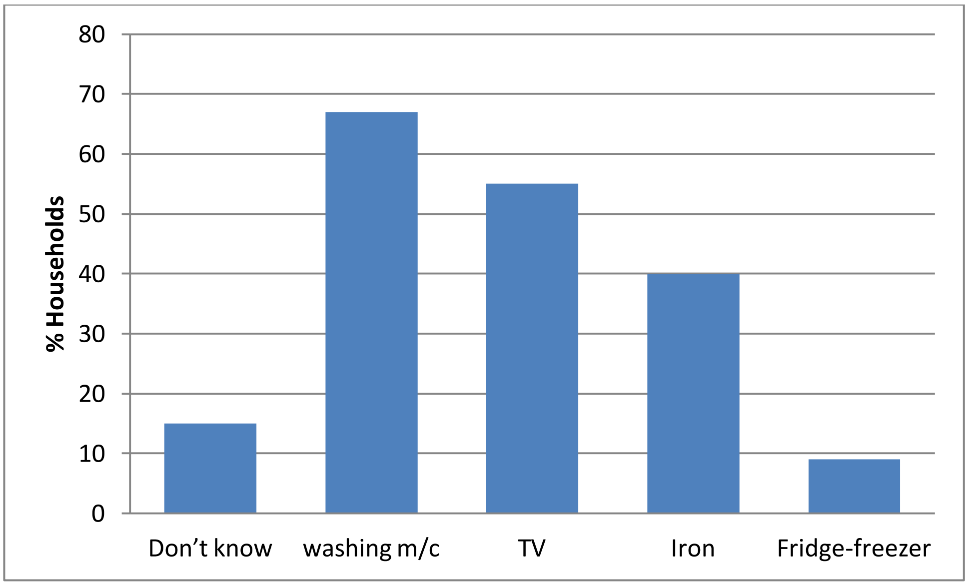


Figure 4. 12 The first appliances households stop using in a constrained situation

4.5 Standby Mode Losses

Some common appliances on standby mode are TVs, cable receivers, stereos, cell phone chargers, microwave ovens, DVD players, Play stations (PS3, PS2) and desktop computers. All these appliances continue to use electricity even when they are off. Worldwide standby power consumes an average of 7 percent of a home's total electricity bill, although that figure is as much as 25 percent in some homes. In developed countries the figure varies from 13% (Australia) to 5% (the United States) (DOE US).

On Fenfushi, the most common appliances left on stand-by were television sets and DVD players. On average, this draws 10 watts of power per appliance, meaning that the total power consumption of all televisions on the island on stand-by mode is more than 1 kW, which is over 3.5% of the off peak demand. Nearly every adult has a mobile phone. Over 80% of the chargers were plugged in all the time, consuming power unnecessarily. Unfortunately the meter used does not register this usage, as the consumption from one charger is too small to be recorded by the meters used. Some studies have shown that mobile chargers use 2.8 Watts in stand-by mode(de Almeida et al. 2011; Firth & Lomas 2009). For any single appliance, the stand-by consumption is low, but adding up the power use of all the appliances on the island, the power consumption of appliances not being used is substantial. It is estimated that it amounts to 2 kW.

4.6 Specific Energy Consumption (SEC)

Specific Energy Consumption (SEC) for industry is defined as the energy consumption per unit of product output. For residential households it is defined as electrical units (kWh) consumed per person per year. The SEC of Fenfushi residents was calculated to be 400 to 480 kWh/person/annum in the year 2007/2008 and is about US$187 per person per annum. The per capita electricity consumption of the outer islands was 175-350 kWh per year in the year 2004. The increase shows penetration of more appliances. SEC for the capital city was around 1100 kWh for the resort islands, with the average being 15400 kWh/bed/yr (van Alphen & Hekkert 2008).

4.7 Quantification by End Use

The loads were disaggregated based on end use, such as lighting, refrigeration, fans, water pumping, washing machine, irons, TV, computer and other common appliances, as shown in Figure 4.13.

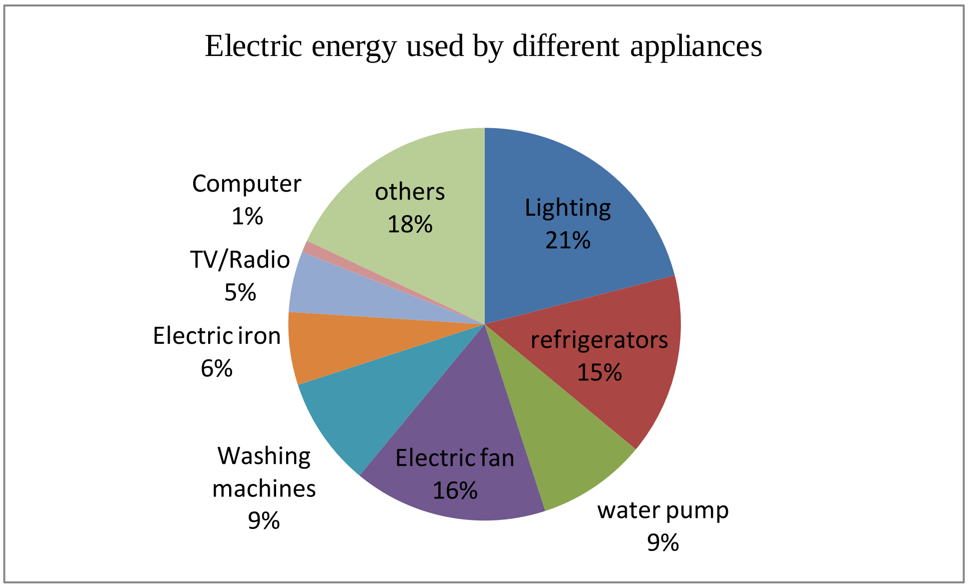


Figure 4. 13 Electricity used by different appliances on the island

4.8 Household Lighting and Fans

There are about 1,500 fluorescent lights and 650 electric fans on the island in total, of which about 575 fans are ceiling fans (the rest are standing fans). Most of the lights are compact fluorescent lights (CFL) of 9-20 Watts. Households also use night-lights of around 5W. The connected fan load is about 53 kW.

4.8.1 Public Lighting

All streetlights are 40W tubes except the lights on the beachfront, which are high power argon, vapour lights of around 250W. These lights are normally operational only in the evenings from about 6 pm to 5 am or 6 am. Table 4.3 shows the number and wattage of street lights used on the island. The number of streetlights, especially the number of normal streetlights, is due to increase as the population extends outwards from the existing area.

Table 4. 3 Streetlights and its wattage

Type/Location	Watts	Number
Beachfront	250	14
Inner roads	40	54

4.8.2 Electric Fans

Most of the ceiling fans have five different settings. Stand fans have three different settings. Ceiling fans draw less power at lower settings of the fan. Table 4.4 shows the basic electrical parameters of a typical ceiling fan used on the island. Typically, ceiling fans are rated at 85W and stand fans at 50W. Utilisation of fans at night when sleeping is common. This is one of the biggest contributors to the average household electricity bill.

Table 4. 4 Sample measurements from a typical ceiling fan used on the island

Fan settings	V(volts)	I(Amps)	P(Watts)	P.F (power Factor)
1	224.7	0.43	41	0.79
2	225.6	0.43	56	0.9
3	223.8	0.45	63	0.95
4	223.4	0.45	66	0.98
ON	223.3	0.45	70	0.99

4.9 Running Water/ Pumping

There is no public water supply to the households. Every household on the island has its own ground water supply in the form of an open well. In over 90% of houses water is piped to different parts of the house by an electric pump. The remaining households use a Dhani[1] to take water from their well.

[1] A cylindrical pot with one open end that is fixed to a stick to take water from the well. The stick is about 5 to 8 feet long and the container can hold 2 to 3 liters of water.

Figure 4. 14 A typical water pump and dhani used on the island

The power rating of the pumps varies from 100 Watts to 450 watts. Figure 4.14 shows a modern house equipped with a water pump and a traditional dhani. The pump usually connects the washing machine, shower and kitchen. However, around half of the households also have an outside tap for general purposes. Utilisation of the pump varies depending on the household's needs. These pumps are normally running whenever there is water running to any of the connected outlets, as there is usually little or no elevated storage capacity. As seen in Figure 4.15, traditional dhanis are still being used in communal water wells.

Figure 4. 15 A typical shallow water well on Fenfushi and a dhani being used

4.10 Refrigeration and Cooling

Nearly every household has at least one fridge-freezer, although some households have more than one and a few have chest freezers. Their usual power rating is 150W-170W when the compressor is running. The compressor running time can be reduced by opening the fridge less often, i.e. only when absolutely necessary (Hasanuzzaman et al. 2008; Liu et al. 2004). It was observed that the compressor runs around one third to one fourth of the time.

4.11 Energy Usage in Cooking

Each of the households is equipped with an LPG stove. Gas is supplied by two local businesses. LPG consumption increased about twofold between 2005 and 2007. On average one and a half bottles of LPG are used per household per month. Nearly half of the households now use one to two bottles per month. The most common LPG bottle size used on Fenfushi is a 10 Kg; other available sizes include 22 Kg and 45 kg bottles.

4.12 Appliance Usage Summary

Every household connected to the mini-grid uses electric lights and fans. On average, households have 9 light fixtures installed. 95% of domestic lights are 13W to 20W compact fluorescent lights, 2% are 2 or 4 feet tube lights and less than 1% is incandescent light bulbs. Every household has 5W night lights that are used when sleeping and that are normally different colours. Almost every household has one or two radios and very often these small radios are operated by batteries. 94% of households have television sets. It is culturally important to have ironed clothes, thus every household owns an electric clothes iron that uses from 1000W to 1200W. The traditional alternative to electric clothes irons were charcoal irons that used charcoal from burning coconut shells and other hard wood. Fridge-freezers and washing machines are common appliances. The domestic water supply is from the individual ground wells and runs with small water pumps of about 100W to 450W.

4.13 Electricity Economics

Here the finances of the energy system of the community will be analysed. There are two main types of costs here: the initial capital investment for installing the generators and the mini grid and the running cost. The running costs of diesel generators include costs of operation and maintenance, and the main component is diesel fuel. These costs are primarily based on the price of diesel fuel, the quality of generator sets and the proper maintenance of the generator system. As with any other generating system, properly trained technical personnel are required for operation and maintenance to ensure the smooth running and durability of the system.

4.14 Electricity Generation Cost

Figure 4.16 shows the variation between the retail price of diesel and the price paid by the country's main diesel importer and distributor, State Trading Organisation (STO). Transportation and delivery to the islands costs an extra 8 US cents per litre on average. The delivery cost values are for the year 2008.

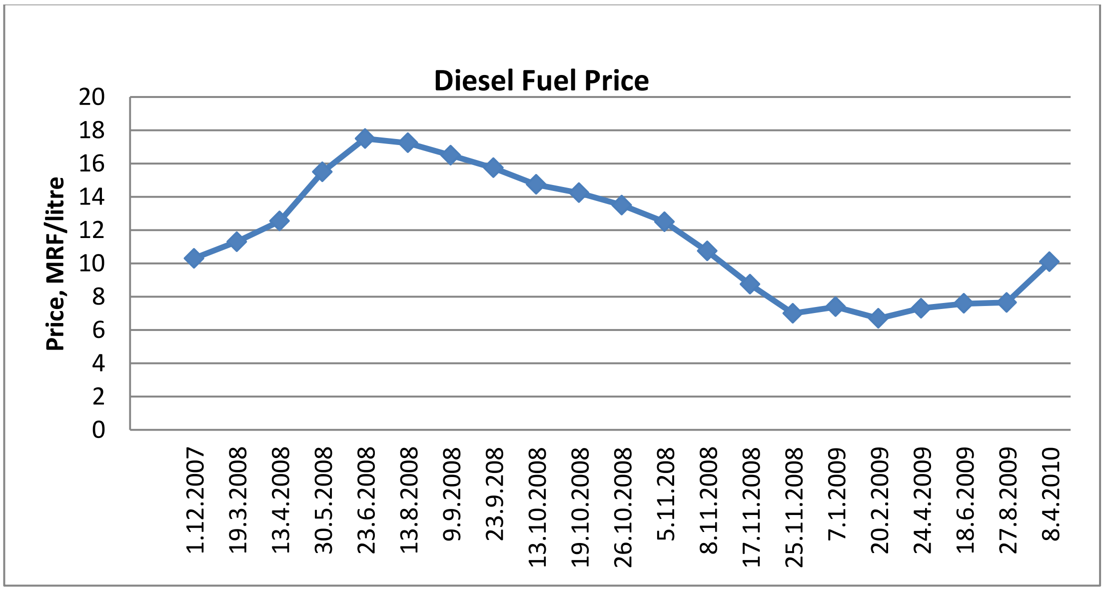


Figure 4. 16 Diesel fuel prices from December 2007 to April 20109. (US$1 =MRF 12.85)

The average monthly diesel consumption of the powerhouse shows a variation of 1,743 litres between October 2007 and August 2008 (see Figure 4.17). There are two possible reasons for this variation: 1) Major industrial work was occurring, such as boat building, with the attendant usage of high energy-consuming electrical power tools like drill machines and sanders; 2) The load in one of the three phases from the generator set exceeded the ampere meter capacity of that phase of the smaller generator, despite overall load being below that capacity. In this case the generator set would stop and manually has to switch to the larger generator, which would be running at a lower efficiency. The existing 160 kW Cummins diesel generator is then put into operation, generating at loads below the capacity of the smaller 40 kW or 60 kW generators. The Cummins set is achieving less than 22.5% efficiency at this level of low load.

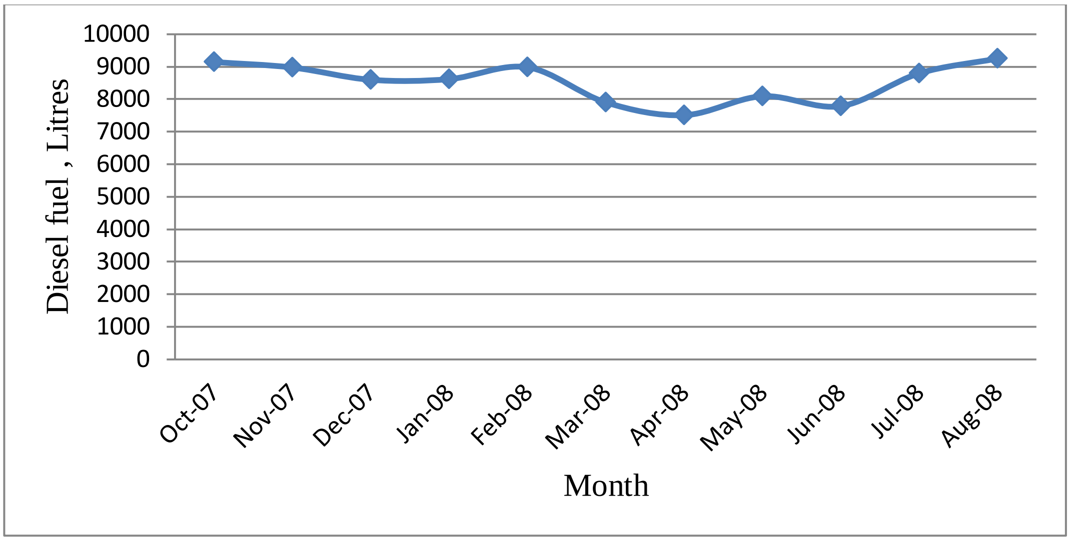


Figure 4. 17 Monthly diesel fuel consumption of island powerhouse from October 2007 to August 2008

Roughly 90% of the operating and maintenance costs are vested in the purchase of diesel fuel and lube oil. The two generator operators are paid about 200 US dollars (or the equivalent) per month. Fuel prices on the island were high at the time of the survey, with diesel retailing for US$1.5 per litre. Average monthly electricity consumptions per household for the first eight months of 2008 are shown in Figure 4.18.

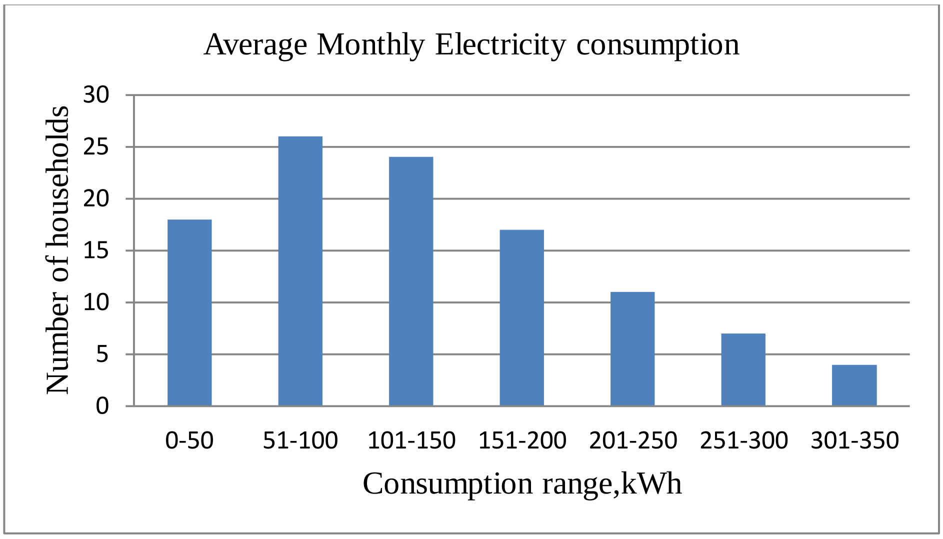


Figure 4. 18 Average monthly electricity consumption of households

The island households are metered and charged based on number of units (kWh) used. The power house runs with subsidies from the Government as the consumer charges do not generate enough funds to meet the operational costs of the power house when selling energy at a rate of 0.4 US$/ kWh.

Chapter 5

Island Energy Resources

5.1 Introduction

Energy resources indigenous to the islands of the Maldives are limited. There are no proven fossil fuel deposits, such as coal, oil or natural gas. Hydro-electric power is not possible due to the low lying nature of these islands and the lack of bodies of fresh water. However, there are some potential renewable energy resources available, such as solar energy, wind power and biomass for cooking. The interviews with the islanders revealed that coconut oil was traditionally used as fuel for lamps before the 1960s; kerosene was then introduced and widely used as late as late the 1990s. The number of coconut trees on these islands has been dramatically reduced over the past two to three decades due to the increasing population and the resultant clearing of forest for housing. Most of the inhabited islands are surrounded by a number of uninhabited islands and these islands are considered in terms of how they could provide resources to the inhabited islands, such as biomass for cooking fuel, sources of food such as coconuts, pandanas, screw pine, bread fruit, etc., and biomass material for building houses. Since the introduction of tourism to the country in 1972 local access to the islands in the tourism development zones has been limited and many of the coconut trees and other plants have been cleared for development; resorts have been developed in almost all parts of the Maldives.

Modelling and observations confirm that mean wind speeds in different parts of the country are good enough for small to medium wind turbines. In the Maldives the wind resource varies very little in exposed areas, but it is important to identify the regions of the country with the better resource so as to find more potential areas for wind power projects. The Maldives is determined to be carbon neutral in a decade and at present most of the electricity generation is planned to be from wind turbines and two projects of one 25 MW wind farm in the south (Addu Atoll) of the Maldives and one 75 MW farm in the central part of Gaafaru Atoll near the capital Male'. These will be close to most of the developed tourist resorts; they have been planned and the initial work is underway. Economic and social factors in addition to the available resource will determine the feasibility of any wind energy project in the country (Elliott et al. 2003).

The sun is a reliable source of energy on these islands but the high humidity of this tropical climate may pose some challenges in exploiting technologies, mainly due to exposed metal parts. The solar and wind energy resources have been analysed and will be discussed in this chapter. Other sources of renewable energies have been discounted because so far they have not been proven to be competitive with wind or solar. There is no literature that supports the viability of contributions from other sources at similar locations. Some other technologies are not mature enough to harness the energy for commercialisation (e.g. wave power, tidal power). In the future, energy from waves could be a potential energy source for these islands but it will take years before this can be implemented.

5.2 Biomass

Plant material and wood were used for cooking on these islands exclusively as late as the early 2000s, with the exception of a few households where kerosene cookers were used. Even today many households occasionally cook using firewood. Coconuts and coconut oil are important for these islanders; the coconut palm is one of the most versatile plants on the islands. The immature (young) coconut is consumed as a drink and it can be used at all stages of maturation for different purposes. The oil from the coconut has been extensively used for the treatment of wood, in particular on timber (wooden) boats. Coconut leaves are used for weaving sheets for house roofing and making baskets and fences. Coconut shells and husks are used for cooking—the charcoal made from the coconut shell is used for grilling fish and in charcoal cloth irons. The fibre from the husk is used to make rope.

Imported synthetic material is now cheaper however and in most cases more durable than rope made from the coconut husk. This has resulted in less demand for locally produced rope, which is rarely produced.

5.3 Wind Resources

A brief literature review on wind resources is attached in Appendix G.

5.4 Maldives/ Island wind data

5.4.1 Weather stations

There are five weather stations in the Maldives, located from the northern most atolls to the southernmost atolls; all the weather stations are located at either a domestic or an international airport. A map showing all weather stations is presented in Figure 5.1. The northernmost station is located on Hanimaadhoo in the south Thiladunmadi atoll, the central station is at Hulu’le (Male’ international airport), and the three remaining stations are in Kadhoo (Laamu atoll), Kadehdhoo (south Huvaduatoll) and Gan (Addu atoll). Gan in the Addu atoll is the southernmost station in the Maldives. Table 5.1 shows the geographical location of the weather stations and their five year average wind speed from 2003 to 2007.

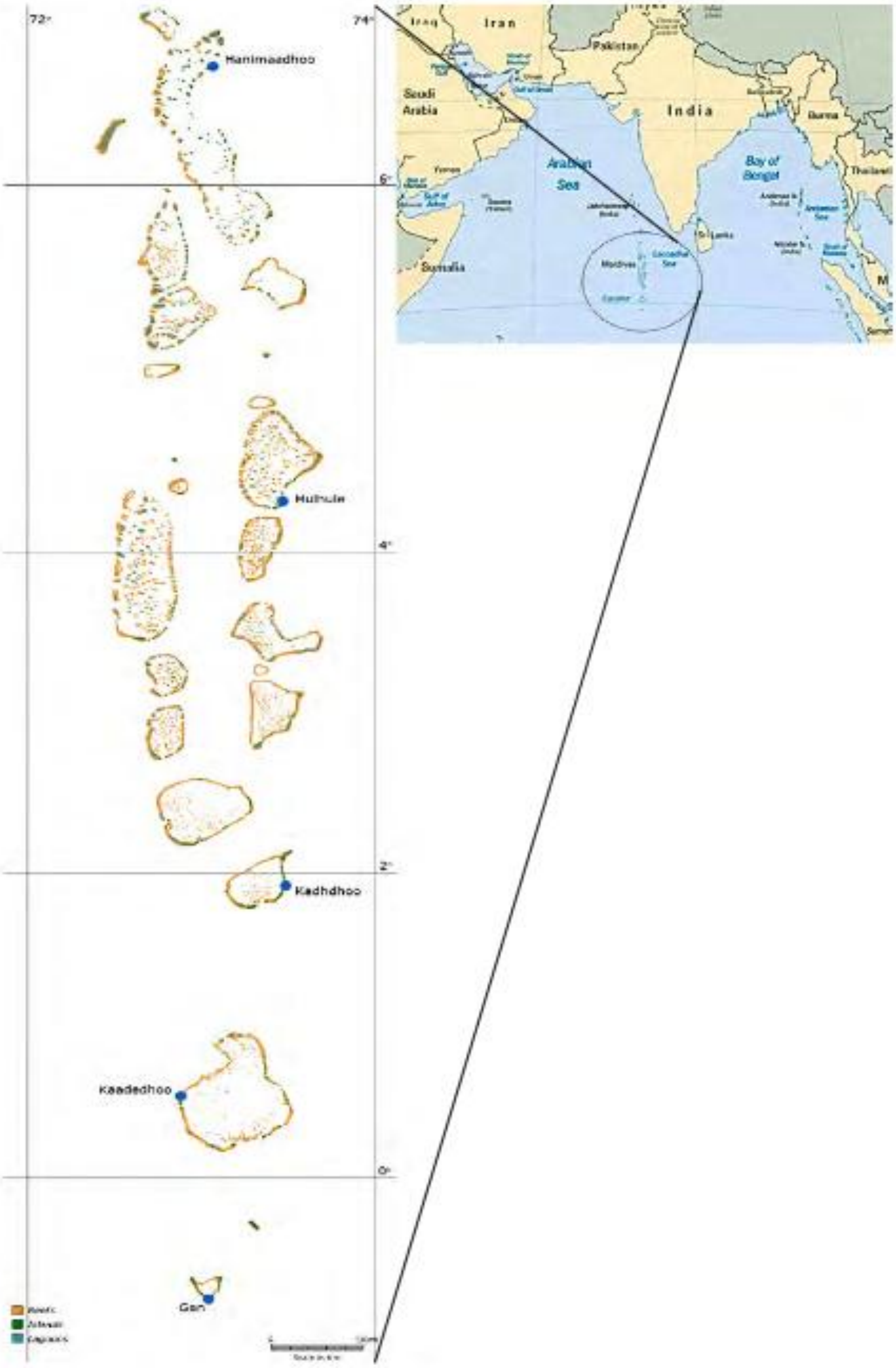


Figure 5. 1 Map of the Maldives showing its natural atolls and local weather observation stations marked with small blue dots

Table 5. 1 Locations of the Maldives' meteorological weather stations

Name	Latitude	Longitude	WS[2](m/s)
Hanimadhoo	6°44'N	73°09'E	4.21
Hulu'le	4°12'N	73°31'E	5.32
Kadhdoo	1°53'N	73°30'E	4.08
Kadehdhoo	0°29'N	72°59'E	3.53
Gan	0°41'S	73°09'E	3.54

5.4.2 The Wind Characteristics at Weather Stations

In this section important wind characteristics recorded at five weather stations will be demonstrated. It is essential to have a good understanding of the wind resources when modelling wind turbines in a power generation system. In the Maldives there has been a good record of wind data for five different locations for a period of five years at ten meter height. This data could be used to generate a fairly good wind profile for most of the other locations, as the general geographic and vegetation are similar. A good wind resource is considered to be blowing most of the days at a significant speed. Wind speed and prevailing wind direction was chosen from the wind data files obtained from Meteorological Department of Maldives. Wind data from five different locations on the Maldives were analysed. The weather stations at these sites use a three-cup anemometer and a wind vane. The measured hourly average wind speeds at 10-m-height for all months of the year are shown in the respective sections.

[2] Five year (2003-2007) average wind speed

The highest resource area in the Maldives extends from just north of Male' to the North Miladhunmadul Atoll and experiences a stronger northeast monsoon from December through February than areas to its north and south. The northwest winds are not as evident as they are further north, with August, September and October having the most northwest winds. March and April are the months with the lowest winds. During December through March the winds are from the northwest replacing the northeast winds observed further north of the country. The northwest winds also re-appear in July and August, though in some years southerly winds prevail during these months. Winds from due west prevail from April through June and in October and November. September is a transition month with characteristics of the westerly and north westerly flow. Months with westerly winds have the strongest winds. The highest wind resource in the Maldives is located where the northeast monsoon is strongest. The west monsoon weakens in the southern part of the Maldives but is of moderate strength down to Addu Atoll. All year round Addu Atoll experiences west winds; it is said that at a location somewhere north of Addu Atoll the monsoon flows stop. The weakening of the west and northeast monsoons results in a pronounced shift of the high wind resource months from the northern to the southern parts of the country, but the moderate west winds across the southern part of the Maldives keep the variation in the overall resource in the Maldives relatively small. During June, July and August the ocean wind speeds are strong with 6 m/s to 7.5 m/s at 10m above the surface. From December to February (northeast monsoon) the wind is of moderate strength, at around 4 m/s to 5 m/s. There is a prevailing northwest wind during the inter-monsoonal months. September and October have significantly stronger northwest winds than March and April.

Important parameters such as monthly mean wind variations, probability distribution function of wind speed, total energy distribution, wind frequency rose, etc for the five weather stations are presented along with the global five year averages (from 2003 to 2007) in Appendix G in graphical form.

5.5 Solar Resource

A good knowledge of local solar radiation is essential for many applications, such as solar energy systems. In spite of the importance of solar radiation measurements, this information is not readily available due to the cost, maintenance and calibration requirements of the measuring equipment (Almorox & Hontoria 2004). This leads to the development of models to estimate solar radiation based on other, more readily available data (Al-Lawati et al. 2003). Different variables such as sunshine hours, air temperature, precipitation, relative humidity and cloudiness have been used in calculating radiation levels (Black 1956; Elagib et al. 1998; Löf et al. 1966). Sunshine duration is the most commonly used parameter for estimation as this can be easily and reliably measured and data are widely available. The solar energy potential of Maldives can be estimated on the basis of sunshine hour data as it is available dating back to 1975 for the central region of Maldives, to 1982 for the southern part (Addu Gan) and to 2004 for the northern region (HDh.Hanimaadhoo).

The following is a description of how to calculate monthly average daily irradiation using one of the commonly used methods, which is known as the modified regression equation of Angstrom's type from daily sunshine hours.

$$\bar{H} = \bar{H}_0 \left(a + b\frac{\bar{n}}{\bar{N}}\right)$$

Where $\bar{H}$ is the monthly average daily global radiation, $\bar{H}_0$ the monthly average daily extraterrestrial radiation of the location of interest, $\bar{n}$ the monthly average daily hours of bright sunshine, $\bar{N}$ the monthly average day length (the monthly average maximum possible daily hours of bright sunshine), and a and b are the empirical constants (location constants).

The monthly average daily extraterrestrial radiation on a horizontal surface ($\bar{H}_0$) can be computed from the following:

$$\bar{H}_0 = \frac{24 \times G_{sc}}{\pi}\left(1 + 0.033cos\frac{360n}{365}\right) \times$$
$$\left(cos\varphi\ cos\delta\ sin\omega + \frac{2\pi\omega_s}{360}sin\varphi\ sin\delta\right)$$

Where G_{sc} is the solar constant (1353W/m^2), φ is the latitude of the site, δ is the solar declination, ω_s is the mean sunrise hour angle for the given month and n is the number of days in the year starting from the January first. The solar declination δ and the mean sunrise hour angle ω_s can be calculated using the following equations:

$$\delta = 23.45sin\left[\frac{360(n + 284)}{365}\right]$$

$$\omega_s = \cos^{-1}[-tan\delta . tan\varphi]$$

For a given month, the monthly average day length $\overline{N}$ can be computed by using the following equation:

$$\overline{N} = \frac{2}{15}\omega_s$$

The values of the monthly average daily radiation $\overline{H}$ are calculated for individual days, which give an average for each month.

Where n is the number of the average day of the month, δ the declination for the mean day of the month, G_{sc} the solar constant (1365W/m^2), $\emptyset$ the latitude and ω_s the sunset hour angle.

5.5.1 Sunshine Hours and Radiation

The following are the sunshine hours and radiation levels calculated for the three mentioned locations in the country.

HDh.Hanimaadhoo

Table 5.2 shows monthly average daily sunshine hours, while Figure 5.2 shows the monthly average daily solar irradiation at Hanimaadhoo weather station from 2004 to 2008.

Table 5. 2 Monthly average daily sunshine hours at HDh. Hanimaadhoo .

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2004	9.7	10.1	9.7	8.2	6.8	7.1	4.8	8.2	5.5	6.3	6.1	7.7
2005	8.3	10.4	10	8.2	8.2	5	6	8.7	6.7	7.6	7.7	7.9
2006	8	10.1	9.7	9.9	6.1	6.3	7.4	7.5	6	6.8	5.2	5.9
2007	9.4	9.6	9.9	9.1	7.3	4.8	5.9	6.4	6.5	6.4	8.7	6.3
2008	9.3	7.4	6.8	8	7.3	4.6	5	7.2	9.1	6.6	7.9	8.3

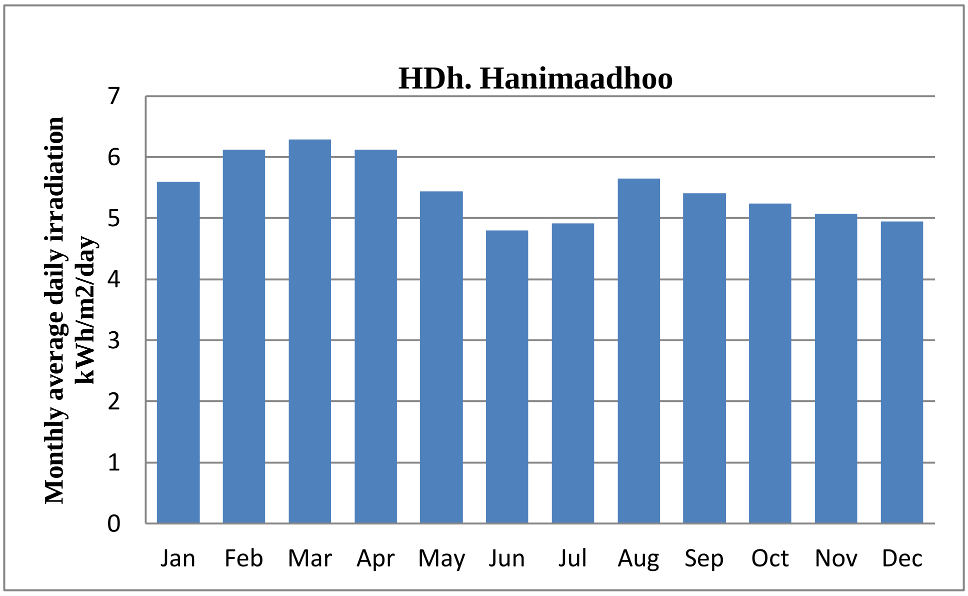


Figure 5. 2 Monthly average solar irradiation for HDh.Hanimaaadhoo (2004-2008)

Hulhu'le

Table 5.3 shows monthly average daily sunshine hours, while Figure 5.3 shows the monthly average daily solar irradiation at Hulhu'le weather station from 1975 to 2008.

Table 5. 3 Monthly average daily sunshine hours at Hulhu'le

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1975	7.9	10.0	10.0	6.6	7.6	5.7	7.8	4.5	7.2	7.6	8.4	8.1
1976	8.3	9.6	10.6	8.2	8.0	9.2	6.8	7.8	8.7	7.6	6.5	8.1
1977	9.6	9.5	9.3	9.0	6.1	8.4	7.2	8.2	7.8	5.9	6.8	5.4
1978	8.8	9.4	8.8	9.2	5.6	6.2	5.8	5.2	6.7	7.8	8.1	6.7
1979	9.3	8.4	9.4	8.7	8.1	6.4	7.8	8.1	5.7	7.7	6.1	7.2
1980	8.3	10.3	9.8	7.8	7.5	8.0	6.6	7.7	7.6	6.5	7.2	7.3
1981	8.4	9.1	7.7	7.8	5.5	7.8	7.7	6.6	5.4	8.2	7.6	7.8
1982	8.9	10.1	9.5	9.1	7.2	5.4	6.6	7.2	5.9	7.2	4.9	4.5
1983	6.7	9.4	8.6	8.3	6.7	6.4	7.3	6.3	4.4	8.1	7.7	6.2
1984	5.8	7.1	7.5	7.3	7.5	6.1	6.8	7.4	7.5	8.5	6.5	9.1
1985	6.8	6.5	8.4	7.2	7.0	5.8	8.7	5.7	6.9	6.9	8.0	6.5
1986	8.5	10.2	7.0	9.0	7.6	7.7	7.8	6.9	5.1	8.7	9.8	5.8
1987	7.3	10.2	10.1	7.7	9.4	6.2	10.1	6.2	7.8	6.5	8.5	7.8
1988	8.6	9.2	8.0	7.9	7.3	6.4	6.9	6.2	6.6	9.5	6.2	7.5
1989	6.2	8.7	10.3	9.2	6.5	6.9	8.4	6.4	7.1	7.5	8.2	8.4
1990	9.3	8.8	9.3	8.9	7.7	6.8	8.3	7.8	8.4	6.9	8.6	6.2
1991	7.8	10.2	9.7	9.0	8.0	7.2	7.0	6.2	7.9	6.0	6.9	6.2
1992	7.5	10.1	10.0	9.2	6.2	5.9	4.3	6.6	7.1	8.8	6.5	6.8
1993	7.2	10.3	9.1	9.3	6.7	7.3	6.3	9.1	7.2	8.7	5.3	6.6
1994	8.6	9.1	8.3	8.6	4.5	6.3	7.5	6.4	6.5	5.4	5.8	6.8
1995	7.9	8.3	9.7	8.4	6.6	6.2	7.4	7.1	8.1	7.5	8.1	7.9
1996	8.1	9.3	9.3	7.6	8.5	5.3	5.5	8.3	7.0	7.4	8.0	9.2
1997	9.6	8.8	9.8	9.2	6.7	8.2	6.2	8.3	6.5	7.2	6.7	5.6
1998	8.1	9.9	9.9	9.7	6.7	6.2	6.4	8.4	6.5	7.7	8.9	4.8
1999	6.5	9.3	8.7	7.9	6.3	7.7	7.4	7.1	7.0	6.8	8.5	7.1
2000	7.4	9.6	8.9	8.2	7.8	5.6	7.9	7.0	5.7	8.4	6.9	8.8
2001	7.6	9.6	10.3	7.8	7.3	7.5	7.4	8.4	6.1	7.3	7.5	7.3
2002	8.1	8.9	8.7	7.3	8.2	7.0	8.0	7.6	8.5	7.5	5.0	5.4
2003	7.9	9.5	8.9	7.8	7.4	5.1	6.6	8.8	6.7	9.7	5.1	8.7
2004	8.8	9.7	10.2	8.8	7.4	9.0	5.3	7.8	5.8	7.5	5.7	6.3
2005	8.7	9.9	9.6	9.2	7.5	7.4	7.0	8.4	6.5	7.1	8.2	8.1
2006	7.9	9.3	8.9	9.8	7.8	7.1	7.5	6.1	6.1	8.1	4.3	3.8
2007	8.6	10.1	9.7	9.2	8.0	6.7	7.0	7.6	6.2	6.4	8.9	6.5
2008	7.9	9.2	7.6	6.9	8.7	7.3	6.3	7.2	9.8	6.7	7.5	7.6

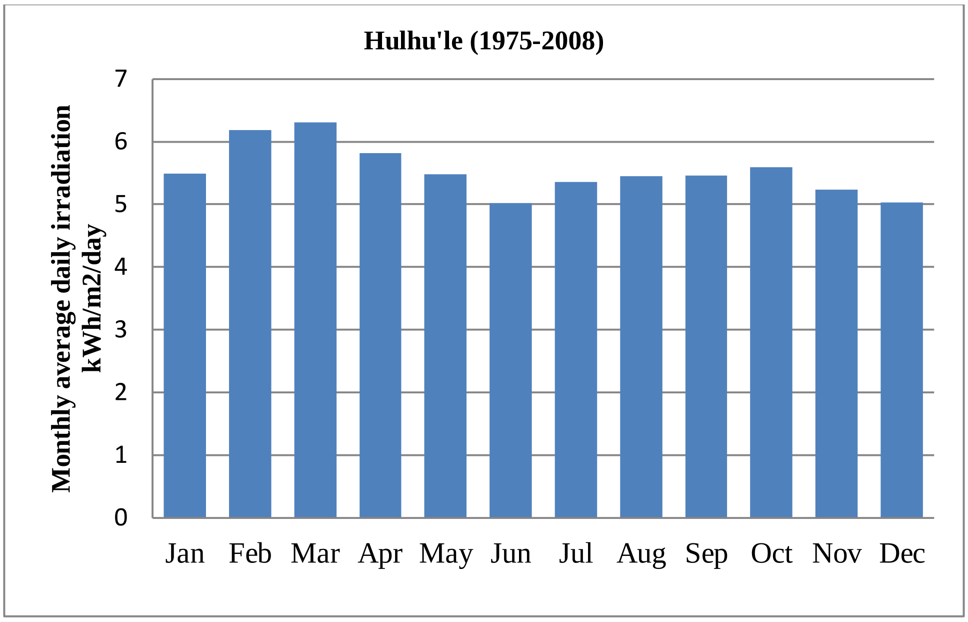


Figure 5. 3 Monthly average solar irradiation for Hulhu'le

Gan

Table 5.4 shows monthly average daily sunshine hours, while Figure 5.4 shows the monthly average daily solar irradiation at Hulhu'le weather station from 1982 to 2008.

Table 5. 4 Monthly average daily sunshine hours at Gan

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1982	10.0	9.6	8.1	8.2	4.0	5.8	8.9	9.9	8.7	6.7	5.5	6.0
1983	7.9	10.3	9.7	8.8	8.7	7.5	7.9	6.3	6.9	4.3	5.5	6.7
1984	9.2	8.6	3.0	6.2	9.2	7.5	4.8	4.8	5.3	7.3	7.7	7.0
1985	7.8	7.0	8.3	7.7	5.7	9.0	8.7	5.6	6.6	7.4	6.5	6.3
1986	7.6	9.5	7.0	8.2	7.4	6.3	7.2	6.6	6.4	6.8	6.5	5.4
1987	6.9	8.3	9.1	7.0	9.5	7.0	7.7	7.3	6.0	5.4	10.0	9.2
1988	7.8	9.2	8.0	7.6	6.7	7.6	6.9	5.6	5.8	7.7	9.4	8.0
1989	5.8	8.7	10.1	8.9	6.0	8.4	5.6	5.4	6.3	4.4	8.7	7.4
1990	7.6	6.7	8.4	8.2	8.1	5.7	7.9	5.7	7.0	4.7	7.9	6.7
1991	7.3	9.6	7.6	8.5	6.7	8.4	7.2	6.7	5.3	5.3	8.4	5.3
1992	6.0	10.2	8.3	8.5	7.5	7.0	6.5	6.8	6.1	7.7	9.2	7.1
1993	6.2	7.7	8.2	8.0	6.9	8.6	6.6	6.8	6.7	7.6	7.5	8.9
1994	7.2	9.5	10.0	8.0	6.8	6.6	6.7	7.1	6.2	6.1	8.0	5.3
1995	7.7	8.9	8.7	8.3	8.2	7.0	6.7	6.1	6.3	7.9	5.5	6.9
1996	9.0	9.3	7.3	8.7	7.5	6.8	4.6	5.5	6.6	6.6	9.1	9.0
1997	8.9	8.5	7.8	8.3	6.1	8.5	7.1	6.7	6.2	7.7	8.6	8.4
1998	7.6	7.8	7.8	8.4	7.0	7.0	5.4	6.1	7.5	6.7	10.3	8.1
1999	6.0	8.8	7.4	9.0	7.2	8.0	8.2	7.0	7.3	7.3	8.2	7.4
2000	7.0	8.1	9.3	8.8	8.4	5.9	6.4	6.9	4.6	8.0	6.0	7.0
2001	9.4	10.1	8.3	7.6	8.8	7.8	6.0	6.8	5.9	6.7	8.6	8.0
2002	6.0	8.2	8.1	7.3	8.7	4.6	5.9	7.2	7.7	6.1	6.6	7.3
2003	7.8	10.0	8.9	6.8	7.9	6.2	6.3	7.4	7.2	9.2	7.7	5.1
2004	6.9	8.7	10.0	7.6	6.8	6.3	6.2	6.9	6.0	7.8	6.7	7.2
2005	6.2	8.5	9.3	8.9	8.1	5.8	6.5	6.4	10.8	6.0	9.8	8.7
2006	8.1	7.3	8.8	8.9	8.6	6.0	6.6	7.6	7.0	7.7	4.7	4.6
2007	6.6	9.7	9.7	8.8	8.2	6.7	6.6	7.3	6.5	6.2	7.5	6.8
2008	7.9	8.3	8.2	7.6	6.9	7.6	6.2	6.5	7.9	6.8	8.5	9.0

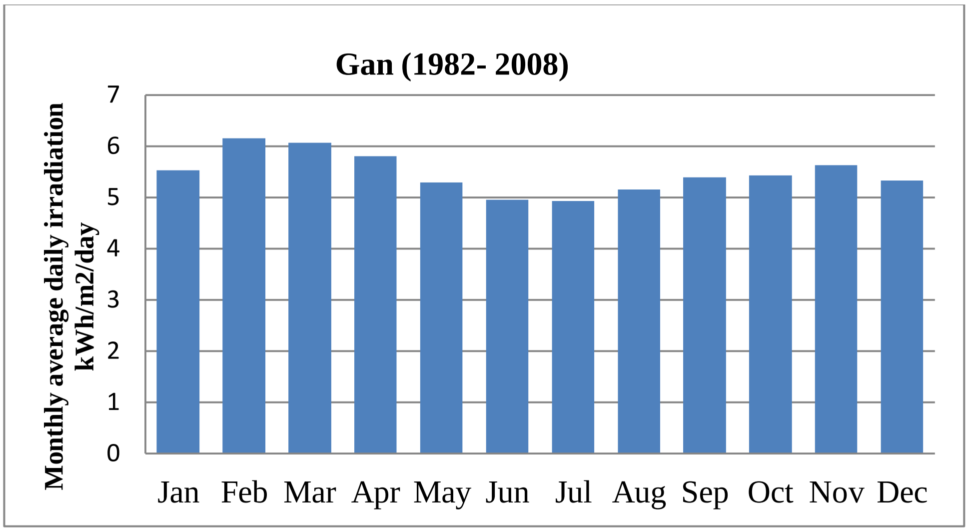


Figure 5. 4 Monthly average solar irradiation for Gan

The solar resource was used for the location 3° 29' N latitude and 72° 47' E longitude. Solar radiation data for this region has been calculated from the available sunshine hours from the weather stations and from the HOMER via the internet. The annual average solar radiation for this area is 5.43 to 5.77 kWh/m2/d. Figure 5.5 shows the solar resource profile of the three locations across the country. It shows that the solar irradiation has a similar pattern throughout the country.

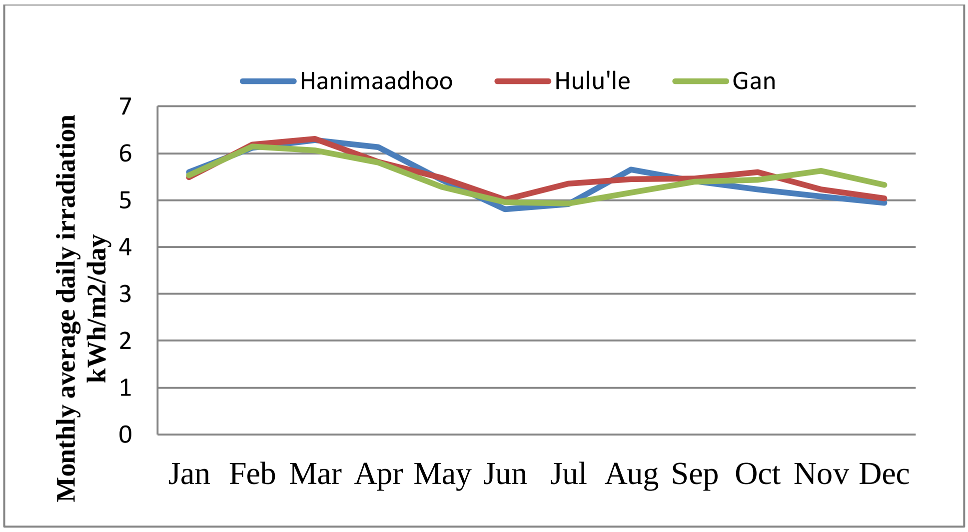


Figure 5. 5 Monthly average daily irradiation for three locations

Chapter 6

Energy Modelling Methodology

6.1 Introduction

The island energy system considered three main load curves for modelling. These were for the existing demand, demand adapted with moderate constraint in fuel supply and demand adapted in a severely constrained fuel supply. The procedures deriving the load for two constrained scenarios are demonstrated; the supply options considered for the analysis include (1) Diesel generators only, (2) Hybrid wind-diesel, (3) Hybrid solar-diesel, (4) Hybrid wind-solar, (5) Hybrid diesel-wind-solar and also using only wind and only PV.

6.2 Reference Load Characteristics

In this section reference energy demands that the two scenarios, namely the necessary and essential loads and the present load, are developed. In the case of necessary and essential demand, the objective is to generate generic electricity load curves that are used as input for modelling to observe the performance of all energy supply system options. For the simulations, noise (random variability) is later applied to these generic load curves. The method for calculating the load curves for the necessary and essential demand is overviewed in Figure 6.1. For the present load curve, the load is the recorded demand from the powerhouse control panel meters. For the two scenarios the electrical appliance penetration data are calculated for each of the households and other institutions and attempted to represent the respective load curve. The hourly load of each household in a randomly taken sample was independently determined based on the appliances power rating and timing of use. To generate the system load curve for the desired scenario, all household and other institutions' hourly demand are added together.

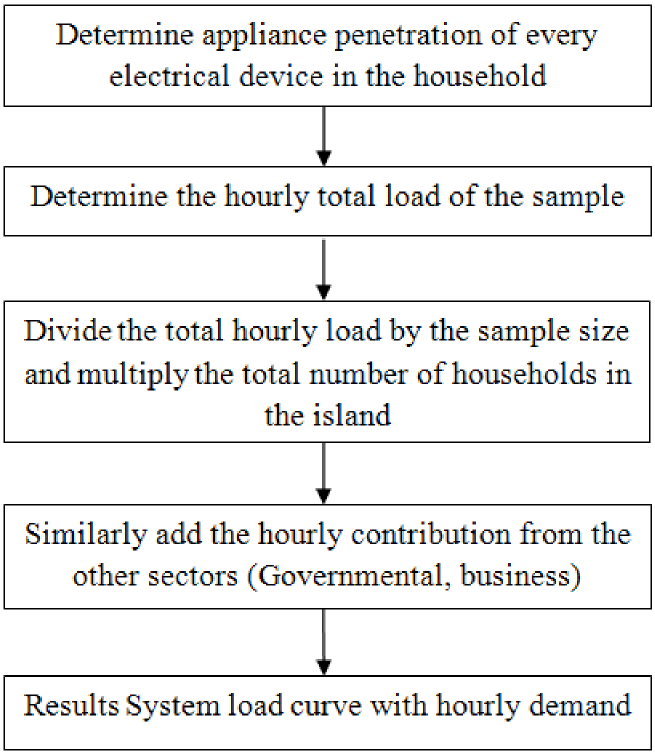


Figure 6. 1 Method to derive the system load curve from a randomly taken sample of households and other institutions

6.3 Growth in Energy Demand

Any growth in demand is not considered in this study. It is assumed that the residents of the island use all the electrical energy they wish as there are no restrictions to what appliances they can use. Even if there is a demand growth and that load falls into the category of optional loads, that may not have significant impact on a constrained situation as long as the load is detachable from the demand when the need arises. In the context of this study, the aim is to find the minimum electrical energy that the residents could use without sacrificing their comfort levels. In the future it is likely that growth will predominantly come with air-conditioning and future air conditioning loads are considered optional. The option of including a constant or any growth year by year is not a function of HOMER therefore if one wants to include any growth a fresh set of simulations has to be run for that load, whether synthetically generated or otherwise. When performing the economic analysis of the configuration for a set number of years, say 20 or 25 years, it is assumed the load remains the same as in the initial year. This might not be true in most of the cases as the general trend is to increase demand year after year. To see changes in economics and feasibility, some simulations based on higher levels of synthetically generated demand could be used. The economic life time for the PV systems are taken as 20 years, unlike many other studies where it is common to take 25 years. This is to account for the high corrosive environmental conditions in the Maldives resulting in deterioration of the metal parts.

6.4 Load Curve of Specific Appliances

A method known as diversified demand curve was used to generate load curves for individual appliances. Appliances such as fridge freezers and electric water pumps in these communities need special treatment to generate their load curves; it is then possible to find the contribution of these components to the overall demand. It is assumed based on the observations made that the fridge freezers run (compressors) one third of the time and all the fridge freezers on the island behave randomly. When it comes to the water pumps it is somewhat different. The usage of these pumps is difficult to calculate. But from the data acquired from the island it was observed that the water use is concentrated in the mornings and in the evening. Since almost every household has small water pump and these pumps run whenever there is a water use as the pumps are not associated with sizable storage. The diversified demand curve of the pumps was generated mainly based on the responses from the residents about the running-water usage pattern. Most people considered water pumps either as an essential or necessary load because they need running water. Considering their need to have running water and at the same time a relief to the generation side to cut down the peaks due to water pumps, a solution is to have an elevated water tank. The average running water requirement for the households is less than 200 litres per day, therefore to put an empty diesel or petrol drum at an elevation is an easy and cost effective solution. Having elevated water storage, the pump loads can be classified as deferrable, which makes generation systems more feasible. In modelling the load curves for the moderately and severely constrained scenarios, the pump loads are taken as deferrable loads.

The average powers of intermittent devices such as fridges or fridge freezers will be a function of the on/off ratio and the power consumption when on. If a fridge or fridge-freezer is on for L seconds and off for M seconds then the average on-time fraction is L/(L+M) and the average off-time fraction is M/(L+M) = 1-(L/(L+M)). Where the room temperature is at 27 to 29 degree Celsius during the day and the fridge-freezer thermostat was set to a medium coolness, it was observed that the compressor runs 25% to 33% of the time. The below example shows how it was calculated:

The fridge-freezer turned off at 9:00 am. Later it turned on at 9:41 am and then turned off at 10:00 am.

L=10:00 – 9:41 = 19 minutes

M= 9:41- 9:00 = 41 minutes

Therefore the time compressor runs at = $\frac{\mathbf{L}}{\mathbf{(L+M)}}$ **=** $\frac{\mathbf{19}}{\mathbf{(19+41)}}$ **= 0.3167** or 31.67%.

The annual cost of running a fridge-freezer (or freezer) will be this fraction of the annual cost if the device was continuously on.

$Cost\ per\ year = 8760 * P * T * \left(\frac{L}{(L+M)}\right)$ Where P is the power rating of fridge-freezer in kW, T is the tariff per kWh.

Average power consumption of some randomly selected fridge-freezers from the island for 24 hours is 0.65 kWh and this gives an average power consumption of 27 watts. Mostly freezers are being used for fish preservation. A detailed refrigeration appliances usage for UK households have been studied by I. Mansouri et al. (Mansouri et al. 1996).

6.5 Electrical Load Profile for Single Households

The electrical load profiles for some of the households were taken and recorded. The load profiles of two of the typical households are shown in Figure 6.2 and Figure 6.3. Figure 6.2 is a household with three bedrooms, two of which have attached bathrooms, a sitting room and a kitchen. There were 3 adults and 2 children living in this household. Figure 6.3 is for a household with five bedrooms housing 9 adults and 4 children. The variation in demand during the 24 hours of a typical day is shown in the Figures 6.2 and 6.3. Observations in are listed below:

1) The load during the night from 10:30 pm to 6:30 am in the morning is considered constant, as a fixed number of appliances are in use, but when the random ‘on’ and ‘off’ of the fridge-freezer is considered its contribution is shown as small peaks.
2) The time at which the ‘night time load’ ends (i.e. occupants wake up) varies from 05:30am to 06:30am for normal school days.
3) The load varies between 0 – 540 W and if an electric iron is in use at the peak time it will add 1.2 kW to the maximum demand.
4) The daily load factor varies between 5.5% and 65%. (Ratio of the average load during the day to the maximum installed load).
5) The time of peak demand varies from 06:30 in the morning to 09:30 in the evening and whenever the electric iron is in use it produces a peak.

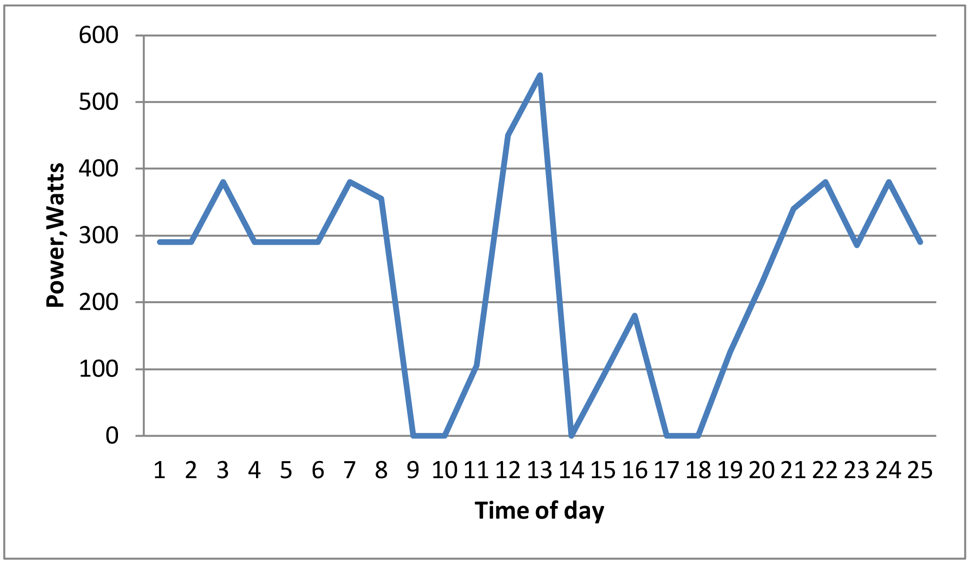


Figure 6. 2 Electric load profile of a typical household with 3 bedrooms

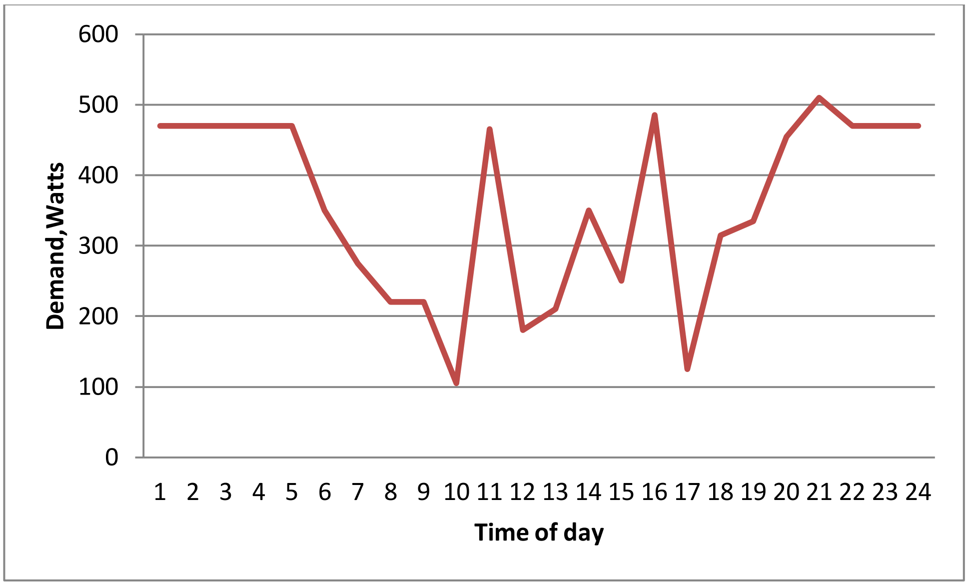


Figure 6. 3 Electric load profile of a typical household with 5 bedrooms

6.6 Generating Load Curves of the Island

It is evident from this analysis that developing methodologies for assessing the total electric load profile of the island community based on individual households would be difficult, as single appliances such as the electric iron contribute a significant load to the system and the use of these appliances is difficult to predict. However, in generating the load profiles of the two constrained scenarios, it was found that most of the high power consuming appliances such as electric irons and ovens are not considered to be essential items and the people who consider these appliances essential or necessary still consider them to be deferrable loads. This makes it easier to determine a household's primary load to generate the load curve and estimate the daily average deferrable load.

Formulations that are used to calculate the hourly contribution of power from different sectors can be found in published texts in the field (Richardson et al. 2009; Rosemann & Suvagau 2008; Tatiétsé et al. 2002; Wright & Firth 2007; Yao & Steemers 2005). Some of the equations are modified and used to calculate the hourly load contribution.

The following are the equations applied to determine the representative load curves and the meaning of the symbols in the equations:

P_{jk} power used by appliance k of household j,

i 1, 2, 3, households, governmental institutions and commercial/industrial sector,

j 1,…, n_i, household,

n_i size of the household sample,

q size of the appliances for household j,

k 1, q, device in use at the time interval/period (electric device or appliance),

N total number of households in the community

Power installed per category (e.g. domestic, public, industrial) is found by applying equation 6.1:

$$p_i = \frac{N_i}{n_i} \sum_{j=1}^{n_i} \sum_{k=1}^{q} P_{jk} \tag{6.1}$$

Total power installed in the defined categories—households, governmental institutions and commercial/industrial buildings—can be presented as the summation of the three categories (Equation 6.2).

$$p_{inst} = \sum_{i=1}^{3} p_i \tag{6.2}$$

The load curve for the island from the three defined categories can be calculated using the Equation 6.3, which is the summation of the hourly loads from the categories.

$$p^t = \sum_{i=1}^{3} \left[\frac{N_i}{ni} \sum_{j=1}^{n_i} \sum_{k=1}^{q} p_{jk}^t \right] \tag{6.3}$$

The described equations can be used to calculate the power installed on the island for the domestic purposes and in other institutions. The load curve can be obtained on a daily, weekly or any other desired periodic basis. The daily variations in the power demanded by the households/community are of particular interest and it was found that the variation is very consistent. The load curve allows knowing consumers behaviour in their electric energy usage for a well established time period. Knowledge of the power variations in particular allows for the sizing of the community network, the computation of excess energy and the identification of the peak usage times. This information is valuable when maintaining the operations and extending the network. The load curve is also important for electrical network management. In fact, each installation must be prepared so as to bring the system to the best possible state, allowing it to perform safely at all times. Calculation of the load curve requires control of the parameters describing the energy demand.

In almost every household, there are two groups of appliances: permanent-use appliances, such as refrigerators and freezers, and short-term or periodic use appliances, such as lights, electric fans, water pumps, irons, mixers, ovens, washing machines, televisions and radios. Two main assumptions are made when calculating load curves: (1) appliances operate at their maximum power rating; and (2) for periodic use appliances, the usage time is considered based on the survey interview results. The usage timing of appliances such as lights and electric fans are very predictable for most of the households and are similar in nature. The load curves for every household have been calculated considering these assumptions. In this way, the load curve for the island community was calculated using Equation 6.3, which represents the contribution from all power consuming sectors in the community. The calculation of the installed power and load curve is not biased, in-so-far as the sample average is an unbiased estimator of the population average of the category, since the expected value of the sample average equals the average of the population it comes from.

The present load curve of a typical day is shown in Figure 6.4, which is unconstrained. Figure 6.5 and Figure 6.6 represent load curves with moderate and severe constraints, respectively. The moderately constrained scenario shows 76 kWh of deferrable load per day with 4 kW of deferrable peak load and the severely constrained scenario shows 35 kWh of deferrable load per day with 2 kW of deferrable peak load. Figure 6.7 shows the differences in the load curves and it is important to note the significant reduction in the severely constrained load curve when compared to the business as usual situation.

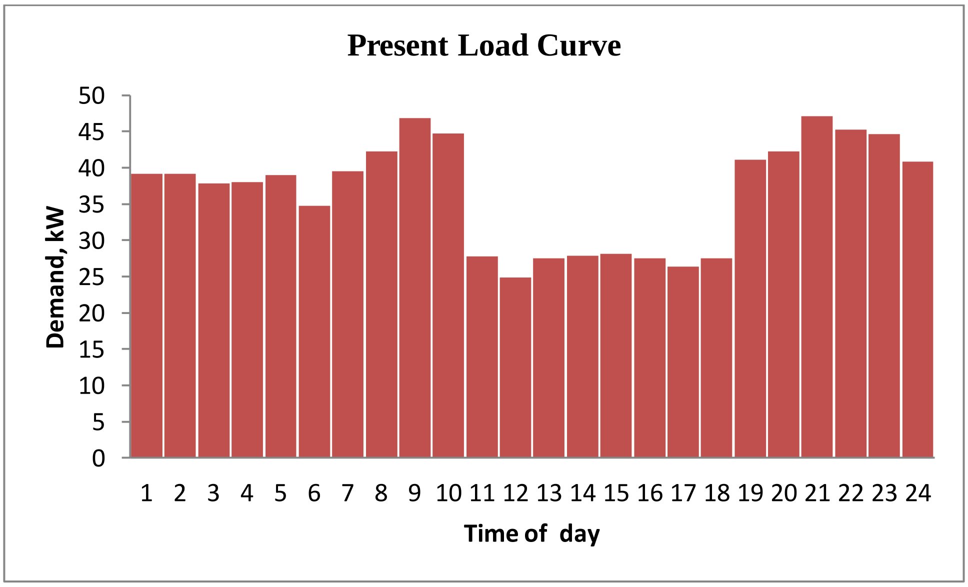


Figure 6. 4 Present unconstrained load profile of the island for a typical day

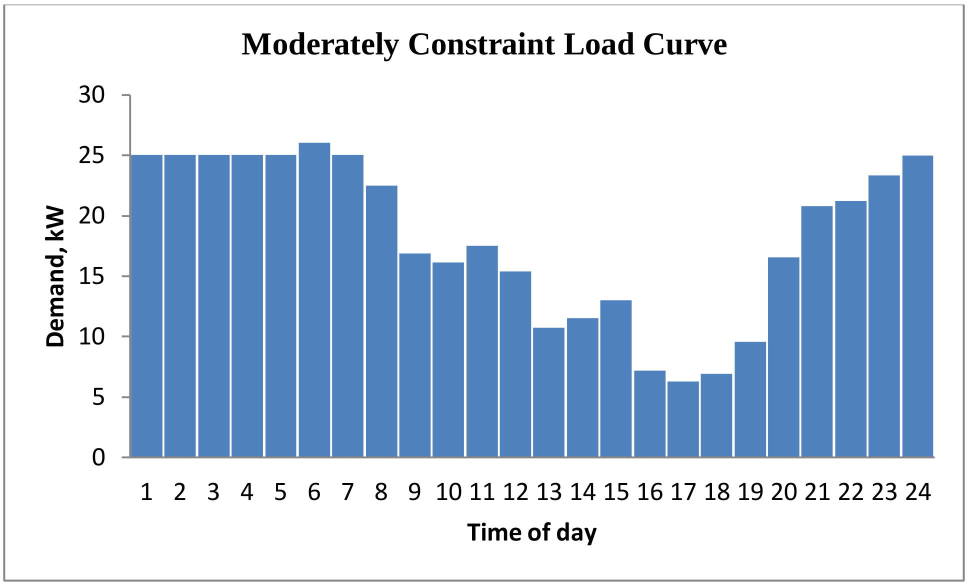


Figure 6. 5 Moderately constrained load profile of the island for primary load

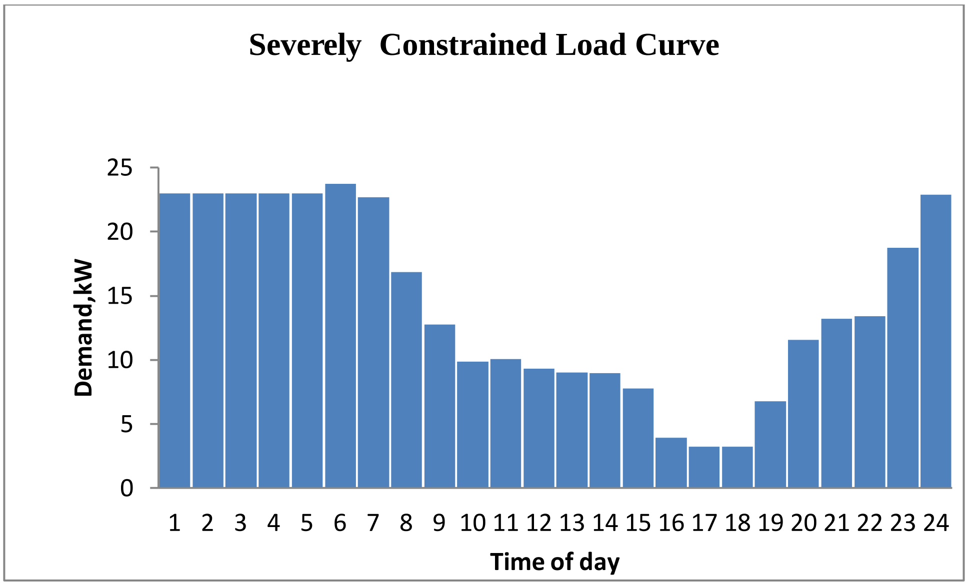


Figure 6. 6 Severely constrained load profile of the island for primary load

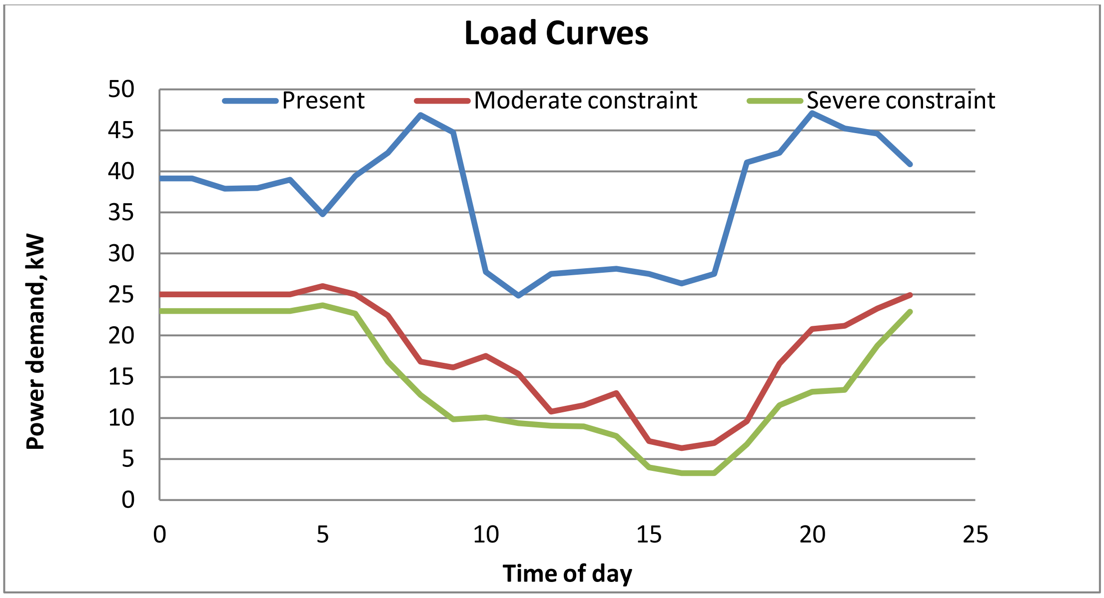


Figure 6. 7 Present load curve and the two modelled load curves for moderately and severely constrained scenarios

Appendix A contains tables detailing a household's hourly electric power demand with both primary and deferrable loads for every household in the sample, and for government institutions and the commercial/industrial sector for both moderately and severely constrained cases modelled using the equations described in this chapter.

6.7 Electricity Loads Summary

This chapter details the process of deriving reference load curves from appliance penetration data, to model the load curves of the two scenarios. The energy demand data of the three load curves are summarized in Table 6.1

Table 6. 1 Electrical load characteristics of the three load curves considered

	Present load	Moderately constrained load	Severely constrained load
Average daily primary load, kWh	888	437	343
Average daily deferrable load, kWh	-	76.3	35
Peak load, kW	47.4	26.1	23.7
Average load, kW	37	18.2	14.3
Load factor	0.781	0.699	0.602
Service hours, per day	24	24	24

Note: Random variability of 10 % considered for the actual hourly load in all cases

6.8 Energy Supply Options

The energy supply options considered for power generation are imported diesel fuel or local renewable resources available on the island. In Chapter 5, two renewable energy resources were identified as promising candidates for implementation: wind and solar power. In order to evaluate the suitability of different energy sources to supply electric loads, these renewable sources are modelled individually, as is the non-renewable diesel option. A number of other hybrid systems are also modelled. In general, hybrid systems are particularly advantageous in energy systems with high solar or wind energy penetration and where energy storage poses a problem either because of cost or other reasons. Thus a total of nine energy supply options are modelled. The options are summarized in Table 6.2.

Table 6. 2 Energy supply system options used for modelling and analysis

Supply options	Resource	Battery Storage
1	Diesel	No
2	Diesel	Yes
3	PV	Yes
4	PV + Diesel	Yes
5	PV + Wind	Yes
6	Wind	Yes
7	Wind + Diesel	Yes
8	Wind + PV + Diesel	NO
9	Wind + PV +Diesel	Yes

Diesel fuel oil energy is stored in the fuel and no external storage is required but for systems with only renewable sources external energy storage is essential, as wind and solar-PV energy systems are intermittent by nature. Hybrid systems with diesel require no or only minimal energy storage for feasible systems but pure wind or solar installations can have substantial energy storage requirements. The only energy storage suitable for the load size in these islands is usually batteries. There are other options such as fly wheels and hydrogen but neither stores large amounts of energy or too expensive.

6.9 HOMER Modelling

In this section, HOMER simulations are performed to find the suitable system sizes of a Diesel/PV/Wind integrated hybrid energy systems with and without battery storage and different combinations of the mentioned sources are considered. The objective function is the minimization of the hybrid energy systems total cost when reliably providing the loads for the residents. The decision variables are PV system size, the number of wind turbines and their sizes, diesel generator sets, the battery capacity, the sizes of other power electronic components such as inverters/rectifiers and the diesel fuel price. The results obtained by the hybrid systems are compared with the results from only using diesel generators and each hybrid system separately. Key modelling inputs and outputs are shown in Figure 6.8. In order to maintain consistency in modelling different concept configurations, the modelling parameters and cost assumptions are established in advance based on realistic values. Generally the same assumptions are used for all models. As seen from the Figure 6.8, HOMER's simulation outputs include various costs, fuel consumption and energy production data.

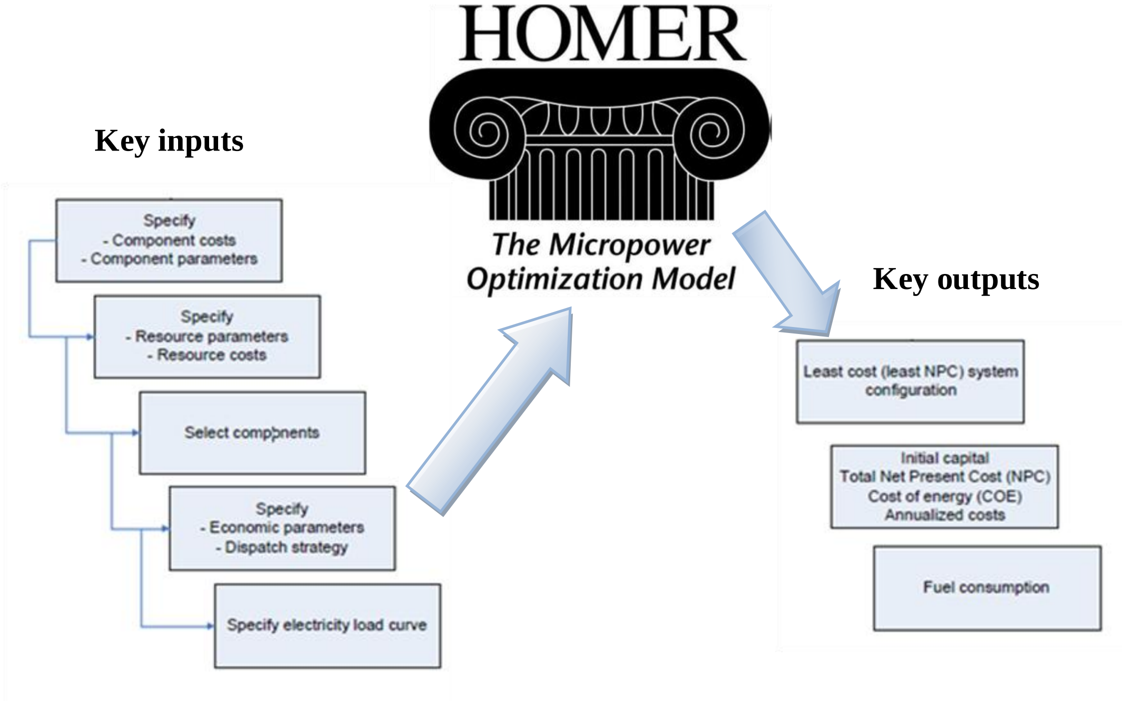


Figure 6. 8 Overview of the key inputs and outputs of the Homer model

Optimization of energy systems in HOMER is based on NPC for chosen constraints and sensitivity variables. HOMER can accept hourly time-step loads and environmental data inputs, providing detailed modelling of the time span examined, while still allowing the assessment of multiple simulations (Lambert et al. 2006). Two important investigative steps when carrying out successful HOMER simulations are assessing the system's technical feasibility in meeting the specified load demand and optimisation of the various configurations based on NPC of the system, which is the total cost of installing and operating the system over its lifetime (Dalton et al. 2009).

For this analysis systems of battery storage, the battery 'cycle charging' strategy was chosen as it increases battery longevity by maintaining the state of charge at required levels (Dufo-López & Bernal-Agustín 2005; Dufo-Lopez et al. 2007). The 'capacity shortage' is the fraction (as a percentage) of the total load, plus any operating reserve that the system fails to supply in a given period. Normally this is an annual value and this shortage can also be referred as an allowable blackout of the system. Two shortage levels of hourly loads were chosen for all system simulations for the present load, which were 5% and 15%. The shortages were allowed only for the present load, as there are a number of appliances considered optional by the residents and the present load curve was recorded without any demand management considerations. The operating reserve constraint was set at 10%, which is the additional reserve capacity required for a system to account for sudden increases in the electric load or sudden decreases in the renewable power output. Higher reserves of 25% for PV and 50% for wind were set for the renewable output. These higher levels are required due to the inherent variability in the output of renewable energy sources.

Output is a list of the lowest cost system configurations among all of feasible technology combinations that were selected to be considered. The optimization parameter is the system's net present cost (NPC), and in HOMER all feasible energy systems are ranked by this value. The NPC is defined as:

$$NPC = \frac{C_{a,tot}}{k_{CRF}}$$

Where $C_{a,tot}$ stands for the total annualized cost and k_{CRF} is the capital recovery factor:

$$k_{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1}$$

Where i is the real interest rate (the interest rate minus inflation rate), and n is the project life time in years. The project life has been taken as 25 years in the context of this study. For financial analysis, the general assumption is that all capital investments and component replacement costs are debt funded. The real interest rate is i = 6.0%, which is the value used for all systems modelling. The total annualized cost $C_{a,tot}$ is the sum of annualized capital cost, annualized replacement cost, annual O&M cost and annual fuel cost. Additional costs used for comparison of the systems are the cost of energy (COE) and initial capital investment. The COE is the average cost per kWh of the electrical load served.

HOMER limitations

HOMER is a computer model that simplifies the task of designing distributed generation systems - both on and off-grid. HOMER's optimization and sensitivity analysis algorithms allow the user to evaluate the economic and technical feasibility of a large number of technology options, and to account for variations in technology costs and energy resource availability. HOMER is an ideal tool for designing village scale power generation programs. Simulation software HOMER has been used extensively in this work for power generation system modelling and the simulations generated hundreds of pages of results that were analysed. Although the software has limitations, most of these could be overcome by recommending that the desired function be included in the software. In carrying out the work for this thesis, a new set of equations as described in section 7.2 were introduced to test the suitability of the power generation systems. These equations were created as the HOMER simulations optimize on the exclusive basis of the Net Present Cost (NPC). The introduced parameter (GAMMA) considers a number of parameters resulting from the simulations, and different weightings are assigned to different components according to the importance of the parameter in the context of this study. HOMER Energy can easily be contacted to introduce improvements to the tool, making it more customised. Furthermore, HOMER has an Application Programming Interface (API) allowing people to write their own source code that can be integrated to carry out the desired tasks in working with HOMER Energy, such as the analysis of the gamma function developed in this thesis.

6.10 Modelling Parameters

In this section the modelling parameters needed for modelling the different power generation systems are discussed. Components include electricity grid and all power supply system components. System component costs are either constant or size dependent. The mathematical modelling of certain components is discussed.

6.10.1 Electricity Grid

Fenfushi has, like most of the other inhabited islands in the Maldives, mini grid installations in working order; all are 240V grids. These mini grids are used for low voltage end user distribution and it is assumed that no investment is required to make these useable. Thus the capital cost for installing the grid is zero for all scenarios. The micro/mini grid with distribution boxes is assumed to be suitable and this set up is more common than having transformers.

6.10.2 Diesel Generator Sets

The cost of diesel generators used in the models is based on the retail price of the local distributors and from publications such as Van Alphen & Hekkert (van Alphen & Hekkert 2008). The cost range variations are shown in Table 6.3.

Table 6. 3 Diesel generator cost ranges from local distributors

Generator Capacity range, kW	Cost range (US$) per kW
10 -25	500 - 1000
25 - 100	250 - 500
100 – 250	150 - 250

In the model, all the generators have an expected lifetime of 20,000 hours, and operate with a minimum load ratio of 30%. It is also assumed that all generators have the same fuel efficiency curve, with an interception coefficient of 0.08L/hr/kW rated and a slope of 0.25 L/hr/kW rated output. These values mean a fuel efficiency of 32% at peak load. While this is a realistic assumption for larger generators, many smaller generators show somewhat lower fuel efficiencies (Hamm 2007; Lasseter & Piagi 2004). For the purpose of modelling, the fuel efficiency curves are considered sufficiently accurate. The operation and maintenance cost of 0.05 US$/hour are considered for all diesel generation. In all hybrid systems with diesel generators, it is assumed if the load requirements are not met by either renewable energy system or by batteries due to state of charge, then load requirements are met by operating diesel generators in the system. To determine the rated capacity of the diesel generators that would be installed in the hybrid system with a renewable source, the following two cases are considered:

1. If the diesel generator is directly connected to the load, then the rated capacity of the generator must be at least equal to the maximum load, and 2. If the diesel generator is used as a battery charger, then the current produced by the generator should not be greater than $C_{Ah}/5$ A, where C_{Ah} is the ampere hour capacity of the battery (El-Hefnawi 1998; Notton et al. 1996).

6.10.3 Generator Fuels

Generators are modelled using diesel fuel oil, as it is the only fuel that could be used to run the existing generator sets. At the time of the survey, the price of diesel fuel in the Maldives varied between US$1 to US$ 1.5 per litre, but since then the price has come down and fluctuated between US$0.8 and US$1.2 between December 2009 and June 2010. Normally this fuel price range is used for modelling systems.

6.10.4 PV Systems

Cost estimates for solar photovoltaic (PV) systems are taken from Van Alphen & Hekkert (van Alphen & Hekkert 2008) . Table 6.4 shows the costs associated with PV systems. The PV system lifetime is assumed to be 20 years, with a PV derating factor of 80%. No tracking systems are employed. All panels are installed with an azimuth angle of 180°. Ground reflectance is assumed to be 20%. PV Systems were modelled up to 6 US$/Watt.

Table 6. 4 Costs of PV systems

PV system components	Cost range (US$)	Unit
Solar PV panel	4.2 – 6.0	W_p
Mounting hardware	10 – 100	m^2
Control system	400 – 600	kW_p
Wiring	200 – 400	kW_p

PV Worldwide Price Variations

Monthly study reports by solarbuzz® (www.solarbuzz.com) from 67 companies and 646 PV models worldwide are shown in Figure 6.9; the mean price of PV modules are in US$/watt and the established price is from worldwide distributors. Exchange rate conversions from local currency in to US dollars are made on the date of each survey.

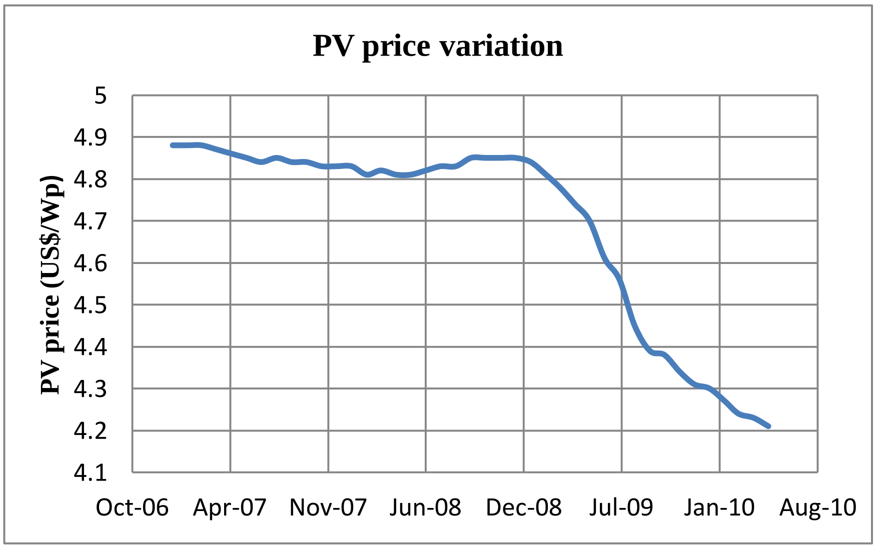


Figure 6. 9 Worldwide PV price variations (source: www.solarbuzz.com)

In May 2010, the mean price of PV was 4.21US$/$W_p$, and it is likely to fall further in the future as production quantity and manufacturing efficiency increase.

6.11 Wind Turbines

Wind turbine prices were modelled according to the prices of commercially available wind turbines. Costs include costs for the turbine, the tower, the turbine controls, the wiring, shipping and installation. Four wind turbines were short listed for the final analysis after a number of initial trials with many other turbines. Price ranges between 3.5 US$/$W_p$ to 5 US$/$W_p$ have been used in the modelling. The latter value is a conservative value and only appropriate for smaller turbines with a rated capacity of less than 5kW. Table 6.5 shows a range of prices for different rated capacity wind turbines suitable for the Maldives. The information is derived from various publications such as Van Alphen & Sark (van Alphen et al. 2007).

Table 6. 5 Price ranges of wind generator components

Wind turbine/Equipment	Cost range (US$)	Unit
Wind turbine (5 - 20 kW)	1500 - 2250	kW
Wind turbine (20 - 75 kW)	750 - 1500	kW
Wind turbine (75 - 200 kW)	500 - 750	kW
Spare parts	1 – 10	%
Control systems	600 - 800	kW
Wiring	200 - 400	kW

Finding Suitable Wind Turbines for the Case Study

The comparison analysis of different wind turbines was performed using an Excel program developed by the Idaho National Laboratory, which has a database with characteristic curves of many wind turbines from the manufacturers. The present load of Fenfushi was used to compare the different wind turbines. The rated capacity restriction of 20 kW was used given the available land area and installation difficulties. Two important parameters were the cut-in and the cut-off speeds, even in this case; the most decisive of the two is the cut-in speed, due to the wind profile of the location. Twelve wind turbines that match these conditions were selected and a simple system was simulated with wind turbines and batteries for the present load curve and evaluated the cost of energy for comparison. Finally the four wind turbines that showed the lowest energy cost were selected for the analysis with other resources.

Table 6.6 shows the different wind turbines analysed to identify the appropriate turbines for Fenfushi's situation and Figure 6.10 shows the characteristic power curves of four wind turbines with different rated powers. The selected turbines were simulated with other resources to find the most appropriate system configurations for the three load curves.

Table 6. 6 Wind turbines analyzed to find the most appropriate ones for the location

Wind Turbine rated Power	**Model**	**Details**	
0.9kW	SW Whisper 100		
	ø: 2.1m	1.294	$/kWh
		1000	wind turbines
1kW	BWC XL.1		
		0.752	$/kWh
		500	wind turbines
1kW	Generic 1kW		
		1.493	$/kWh
		1000	wind turbines
1kW	SW Whisper 200		
		0.69	$/kWh
		500	wind turbines
1.8kW	SW Skystream3.7		
	ø: 3.7m	0.664	$/kWh
		200	wind turbines
2.5kW	WES 5 Tulipo		
	ø: 5m	0.554	$/kWh
		150	wind turbines
3kW	Generic 3kW		
		1.937	$/kWh
		500	wind turbines
3kW	SW Whisper 500		
	ø: 2.1m	0.666	$/kWh
		100	wind turbines
7.5kW	BWC Excel-R		
		1.041	$/kWh
		100	wind turbines
10kW	BWC Excel-S		
		1.471	$/kWh
		100	wind turbines
10kW	Generic 10kW		
		1.496	$/kWh
		100	wind turbines
20kW	Jacobs 20kW		
		1.405	$/kWh
		50	wind turbines

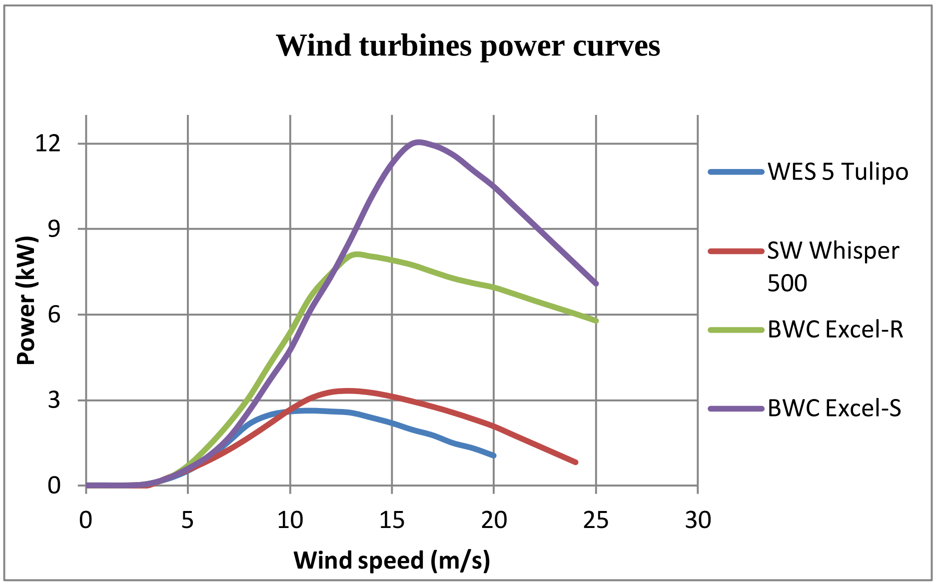


Figure 6. 10 Characteristic power curves of turbines with different rated powers.

HOMER chooses the WES 5 Tulipo wind turbine over other turbines as it functions efficiently at the average wind speed of the location. Apparently other turbines like BWC Excel-S would have been chosen by HOMER if the average wind speed of the site was about 10 m/s. Consequently the characteristic curves of the turbines must be carefully entered if that turbine is not included in the HOMER library.

6.12 Power Converters

Power converters are instrumental in systems that involve changing AC to DC or DC to AC. It allows for the storing of the excess energy produced by the wind turbines or PV arrays and also provides energy from the storage batteries when the energy sources are not able to meet the demand. An AC current of 230V is converted to a DC current of 12V and vice versa. A mean price value of 110US$/kW was set, which is very low in comparison with the other elements of the system. Solar PV, most of small wind turbines and most of the battery banks all work with DC electricity. In order to be useable for the island grids, it needs to be converted to AC power by inverters. For this purpose, all inverters must be of the intertwine type, i.e. be capable of frequency synchronization. Inverters also include rectifier (AC/DC) capability. Costs for inverters are assumed to include costs for transport and installation, and also controlled dump loads. Converter systems are modelled with a constant efficiency of 95% and a system lifetime of 15 years.

6.13 Battery System

A battery bank is considered as the only suitable medium of energy storage for this case study. Batteries of different electrical characteristics, size, weight and price were studied. It was found that Hoppecke 24 OPzS3000 and Rolls (Surrette 460) were suitable to be used for the systems with solar and wind energy. These two types of batteries were modelled in HOMER to find the final selection. Table 6.7 shows important characteristics of these two batteries.

Table 6. 7 Characteristics of batteries considered for modelling

Characteristics	**Hoppecke 24 OPzS**	**Surrette S460**
Nominal voltage (V)	2	6
Nominal capacity (Ah)	3000	460
Nominal energy (kWh)	6	2.76
Lifetime (kWh)	10196	1394
Weight (kg)	246	53.1
Volume (m^3)	0.1016	0.0253
Price (US$)	2100	300

Finally due to the compactness, weight and nominal voltage, Surrette S460 batteries were used for system comparisons. The electrical characteristics of the S460 battery are shown in Figure 6.11 and Figure 6 .12.

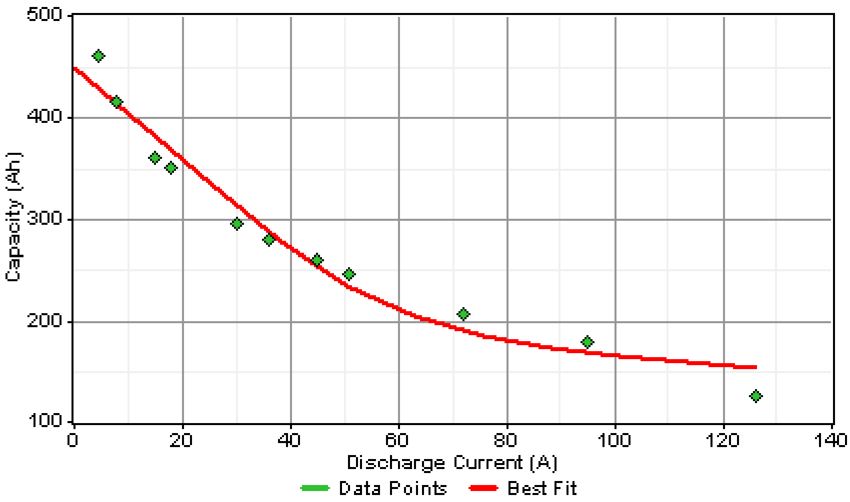


Figure 6. 11 Battery (S460) characteristics curve showing capacities at discharge rates

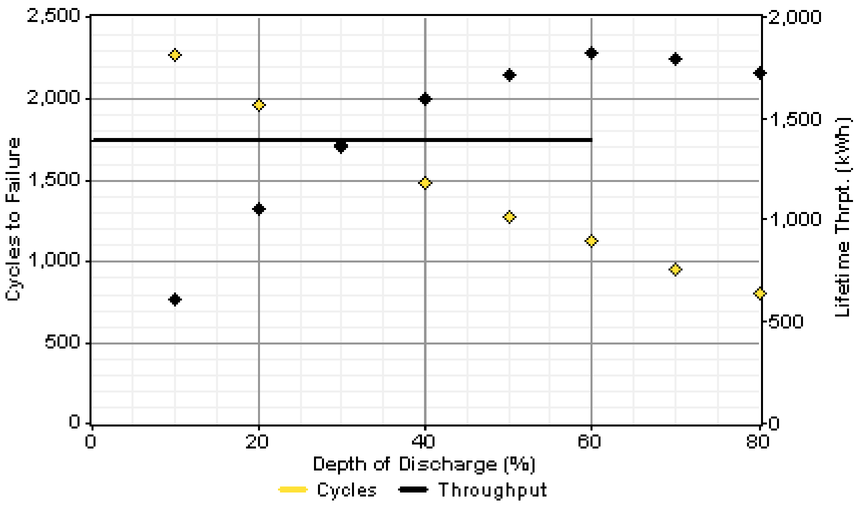


Figure 6. 12 Battery (S460) characteristics curve showing capacities at discharge rates

Mathematical modelling of battery

In a fully renewable system, battery storage is sized to meet the demand during non-availability period of renewable energy sources, commonly referred to as days of autonomy. Normally days of autonomy are taken to last 2 or 3 days (Deshmukh & Deshmukh 2008a) but the number of days very much depends on the weather condition of the location and the level of security sought. The number of autonomy days could be increased if there are long periods of overcast and calm. Battery sizing depends on factors such as maximum depth of discharge, temperature correction, rated battery capacity and battery life. Required battery capacity in the ampere hour is given by:

$$B_{rc} = \frac{E_{c(Ah)}D_s}{(DOD)_{max}\eta_t}$$

Where $E_{c(Ah)}$ is the load in ampere hour, D_s is the battery autonomy or storage days, $(DOD)_{max}$ is the maximum battery depth of discharge, η_t is the temperature correction factor (Bhuiyan & Ali Asgar 2003).

The difference between power generated and load determines whether battery is in charging or discharging state. The charge quantity of a battery bank at the time t can be calculated by:

$$E_B(t) = E_B(t-1)(1-\sigma) + \left(E_{GA}(t) - \frac{E_L(t)}{\eta_{inv}}\right)\eta_{battery}$$

Where $E_B(t)$ and $E_B(t-1)$ are the charge quantities of the battery bank at the time t and $(t-1)$, σ is the hourly self-discharge rate, $E_{GA}(t)$ is the total energy generated by renewable energy source after energy loss in controller, $E_L(t)$ is load demand at the time t, and η_{inv} and $\eta_{battery}$ are the efficiency of the inverter and charge efficiency of battery bank (Ai et al. 2003). The charge quantity of the battery bank is subject to the following constraints:

$$E_{B_{min}} \leq E_B(t) \leq E_{B_{max}}$$

Where $E_{B_{max}}$ and $E_{B_{min}}$ are the maximum and minimum charge quantities of the battery bank.

6.14 Simulated Result

In this section the simulated results are presented for each of the three load curves. A set of nine system configurations are simulated for each of the curves. Important outcomes regarding the ability of each of the systems to supply the respective demand are presented in this section.

6.14.1 System Configurations to Supply the Present Load

All system modelling on the present load is based on the assumption that the load at the time of the survey exists for the island community of Fenfushi. The electric load for the existing 78 households and other institutions on the island has been used as the demand for the present load. In the results presented, the existing diesel generator sets have not been modelled, as that was not a suitable system configuration. The results are based on the HOMER simulation outputs.

6.14.1.1 Diesel Only Systems

With Proper Generation System Components

Similar to the present generation system, this system will also use diesel fuel oil for generation but with appropriate system size components with respect to the demand (assuming that the flaws in the phase balance of the existing system have been rectified). All three phases of the generators are balanced and over-capacity generators are replaced with appropriately sized units. System schematics are shown in Figure 6.13 and system details are summarized in Table 6.8 and Table 6.9.

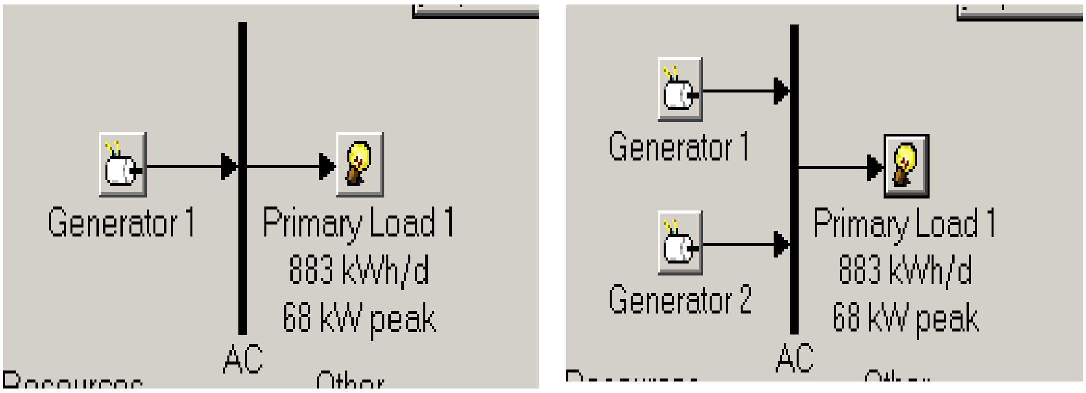


Figure 6. 13 Schematic of diesel only systems to supply the present demand (one generator and two generator systems)

Table 6. 8 System details with one diesel generator to supply the present load

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Diesel L/yr	Shortage %
153,013	1,965,301	9,278	0.477	124,026	0
137,402	1,764,595	8,131	0.436	111,403	5
136,086	1,747,695	8,060	0.434	110,330	6

The system consists of a 62 kW generator set for no shortage, 46 kW generator set for a 5% shortage and 45 kW generator set for a 15% shortage; even though a 15% shortage was allowed, the real shortage was only 6%.

Table 6. 9 System details with two diesel generators to supply the present load

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Diesel L/yr	Shortage %
142,638	1,840,013	16,621	0.447	115,865	0
135,807	1,749,034	12,967	0.432	108,941	5
124,716	1,606,688	12,394	0.425	99,706	15

The system consists of 41 kW and 56 kW generator sets for no shortage, 10 kW and 36 kW generator sets for the 5% shortage and a 4 kW and 34 kW generator sets for the 15% shortage.

6.14.1.2 Diesel Systems with Battery Storage

Figure 6.14 shows the schematics of diesel generators with battery storage. Table 6.10 and Table 6.11 shows system details with one and two diesel generators, respectively.

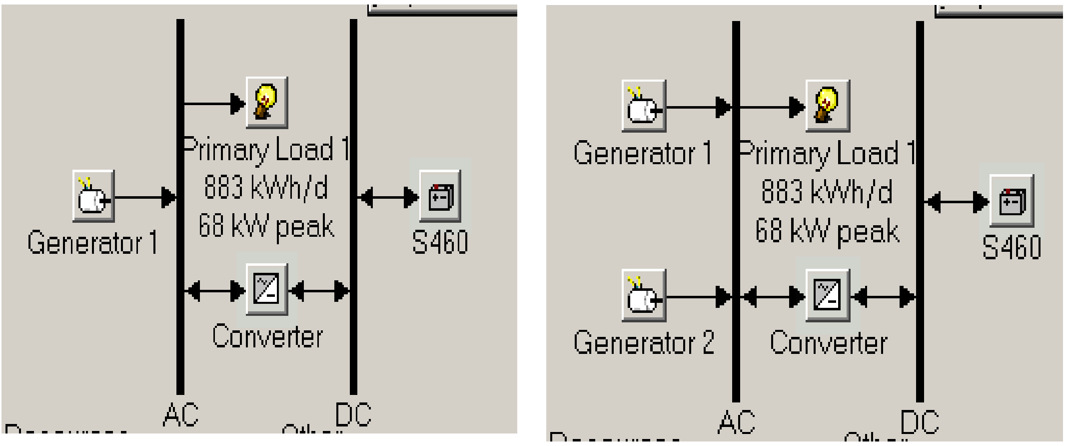


Figure 6. 14 Schematics of diesel systems with battery storage to supply the present demand

Table 6. 10 System details with one diesel generator and battery storage for the present load

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Diesel L/yr	Shortage %
140,570	1,828,845	31,886	0.444	112,570	0
135,618	1,747,146	13,493	0.434	108,899	5
123,780	1,597,475	15,147	0.427	99,206	15

With no shortages in supply a diesel generator of 44 kW and 70 batteries would cater to the present load. With a 5% shortage it requires a diesel generator of 42 kW and 15 batteries, whereas with a 15% shortage a 36 kW diesel generator and 20 batteries are required.

Table 6. 11 System details with two diesel generators and battery storage for the present load

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Diesel L/yr	Shortage %
138,573	1,793,908	22,485	0.436	110,254	0
135,343	1,747,036	16,901	0.434	106,985	5
125,564	1,620,839	15,712	0.430	98,906	15

Simulations with two diesel generators and no shortage require 13 kW and 37 kW diesel generators with 25 batteries. 5% supply shortages require 9 kW and 34 kW diesel generators with 10 batteries and a 15% shortage requires 6 kW and 31 kW diesel generators with 10 batteries.

6.14.1.3 PV and Battery System

Figure 6.15 shows the schematic of the supply system with solar PV and battery storage. Table 6.12 gives important system details.

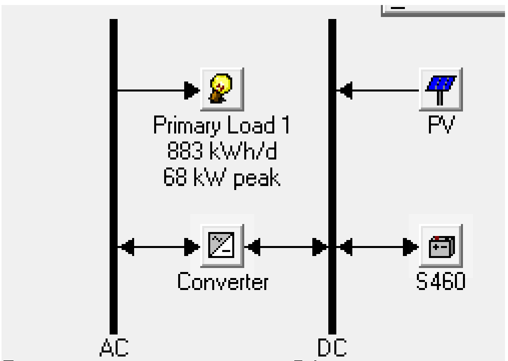


Figure 6. 15 Schematic of PV-battery system to supply the present demand

Table 6. 12 System details with PV and battery system for the present load

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	PV size (kW)	Shortage %
61,949	2,660,692	1,868,782	0.646	1920	305	0
44,394	2,078,303	1,510,798	0.527	1,290	265	5
39,592	1,812,513	1,306,398	0.504	1170	225	15

To supply the island power using a solar PV system, a very large battery storage would be required. The size of the solar PV panels required covers roughly 2,000 m^2

of land area without supply shortages. This could not be taken from the roof tops of different government institutions such as the island school, island office, power house, etc. The school has got enough area on its roof for about 45 kW PV, which is about 100m from the power house where the main control system could be placed. This would minimise the wiring material cost and other places like the island court, the new mosque, the old mosque and the youth centre would be suitable places for PV installation. Finding a suitable area for this capacity would be challenging without clearing a sizeable area from the remaining small forest.

6.14.1.4 PV-Diesel- Battery System

For this configuration a 45 kW diesel generator and diesel fuel consumption of 87,364 litres are required without any supply shortage. Allowing a 5% shortage still the system runs with a 45 kW generator set but no batteries are required, but burns 105, 232 litres of diesel fuel annually. Allowing a 15% shortage the system requires a 35 kW generator set and burns 88,085 litres of diesel fuel. Figure 6.16 shows the system schematic and Table 6.13 gives important system details.

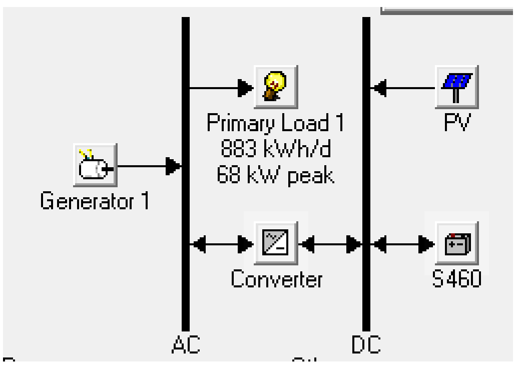


Figure 6. 16 Schematic of PV-diesel-battery system to supply the present load

Table 6. 13 System details with PV-diesel-battery system to supply the present load

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	PV (kW)	RE %	Shortage %
112,659	1,706,002	265,841	0.414	70	55	25	0
130,691	1,743,612	72,941	0.31	-	15	7	5
111,874	1,572,662	142,542	0.418	20	30	15	15

6.14.1.5 PV-Wind-Battery System

The initial capital required for this system of 100% renewable energy sources makes it unattractive, even though the cost of energy is comparable with diesel hybrid systems. Figure 6.17 shows the system schematic and Table 6.14 gives important system details.

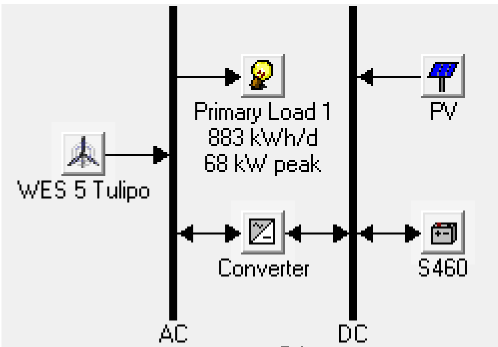


Figure 6. 17 Schematic of PV-wind-battery system to supply the present load

Table 6. 14 System details with PV-wind-battery system to supply the present load

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	PV (kW)	WT Nos.	Shortage %
42,679	1,992,582	1,446,998	0.484	975	185	42	0
33,140	1,517,700	1,094,065	0.383	730	125	39	5
27,111	1,133,855	787,282	0.311	575	55	43	15

6.14.1.6 Wind-Battery System

A system with only wind turbines has been modelled. As wind is an intermittent source of energy by nature, to model without any storage would be economically infeasible, therefore it is modelled with reasonable battery storage. Large amounts of excess energy are being generated with wind turbines. With no shortage, the excess electric energy is 1,137,586 kWh per year and with 5% and 15% shortages the excess energy is 568,897 kWh and 216,520 kWh per year respectively. Figure 6.18 shows the system schematic and Table 6.15 gives the system details.

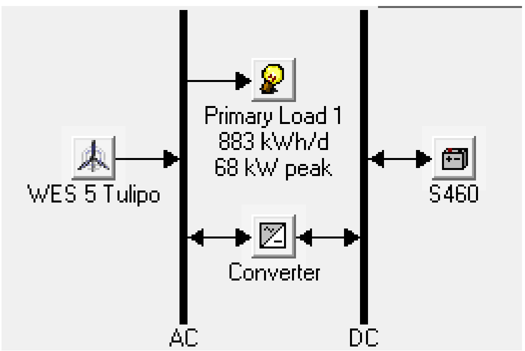


Figure 6. 18 Schematic of Wind-battery system to supply the present load

Table 6. 15 System details with Wind-battery system to supply the present load

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	WT Nos.	Shortage %
80,631	3,172,961	2,142,232	0.771	1395	195	0
50,546	1,975,942	1,329,798	0.499	895	120	5
32,853	1,243,176	823,198	0.341	646	71	15

6.14.1.7 Wind-Diesel-Battery System

This system operates with a diesel generator set of 40 kW consuming 55,869 litres of diesel fuel annually and a renewable energy contribution of 59 percent with no shortage. Allowing a 5% shortage, a 30 kW generator burns 55,489 litres of diesel fuel and the renewable energy contribution is 58%. The actual annual shortage is 4% though 5% was allowed. With a 15% shortage the system uses a 20 kW diesel generator set and burns 35,824 litres of diesel and the renewable energy contribution is 71%. Figure 6.19 shows the system schematic and Table 6.16 gives the system details.

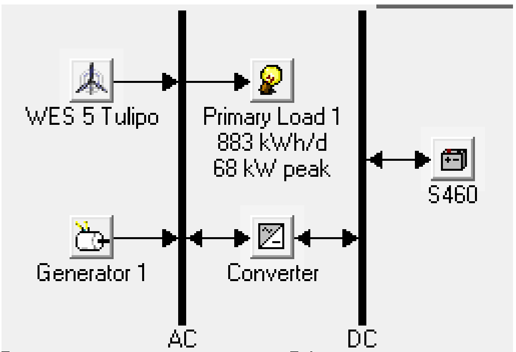


Figure 6. 19 Schematic of Wind-diesel-battery system to supply the present load

Table 6. 16 System details with wind-diesel-battery system to supply the present load

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	WT Nos.	Shortage %
80,207	1,347,327	322,017	0.327	130	31	0
80,718	1,329,063	297,217	0.331	110	29	4
62,858	1,177,537	374,000	0.318	240	33	15

6.14.1.8 Wind-PV-Diesel System

This system does not consider any PV components for the lowest NPC. Renewable contributions of 65, 60 and 64% are observed with no shortage, 5% and 15% shortages respectively. The diesel generator capacity was 60 kW and burns 79,145 litres annually with no shortages. Basically the system acts as a wind-diesel supply system. Figure 6.20 shows the system schematic and Table 6.17 gives system details.

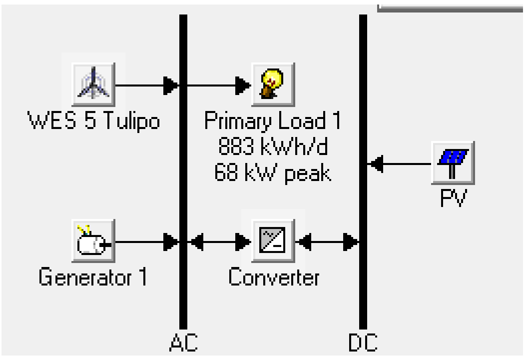


Figure 6. 20 Schematic of wind-PV-diesel system to supply the present load

Table 6. 17 System details with the wind-PV-diesel system supplying the present load

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	PV(kW)	WT Nos.	Shortage %
108,339	1,779,066	394,134	0.432	-	44	0
93,397	1,516,634	322,702	0.375	-	36	5
78,057	1,319,818	321,985	0.347	-	36	15

6.14.1.9 Wind-PV-Diesel-Battery System

With no shortage a diesel generator of 40 kW and 170 batteries (S460) was considered with 58% renewable energy. With a 5% shortage a 60 kW diesel generator and 520 batteries was considered with 78% renewable energy. With a 15 % shortage a 15 kW diesel generator set and 500 batteries was considered with 82%

renewable energy. Figure 6.21 shows the system schematic and Table 6.18 gives system details.

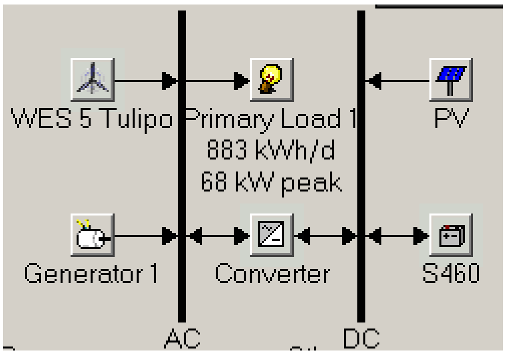


Figure 6. 21 Schematic of wind-PV-diesel-battery system to supply the present load

Table 6. 18 System details with wind-PV-diesel-battery to supply the present load

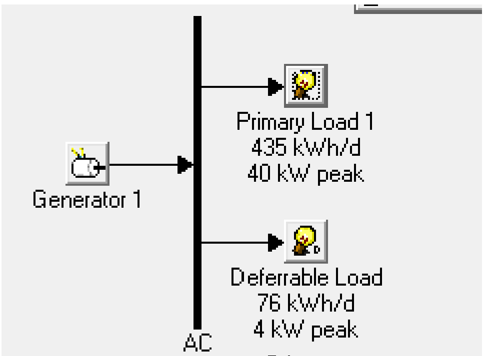
Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	PV(kW)	WT Nos.	Shortage %
79,724	1,346,934	327,793	0.327	0.6	30	0
60,599	1,294,266	519,609	0.324	-	40	5
48,673	1,123,229	501,027	0.305	1.2	38	15

6.14.2 Results of the Systems Modelled for the Moderately Constrained Demand

Unlike the systems for the present load, when modelling the systems for the moderately constrained demand scenario no shortages in supply were allowed as the load was considered either necessary or essential. Also unlike the previous systems, deferrable loads were separated from the primary load. For moderately constrained demand, deferrable peak loads of 4 kW, 6kw and 8 kW were used as sensitivities.

6.14.2.1 Diesel Only Systems

The system with one diesel generator was considered with a 35 kW diesel unit, while the system with two generators was consider with a 25 kW and a 10 kW unit to supply the required demand of the community. Figure 6.22 shows the system schematic and Table 6.19 and Table 6.20 give the system details for one generator and two generator systems respectively.



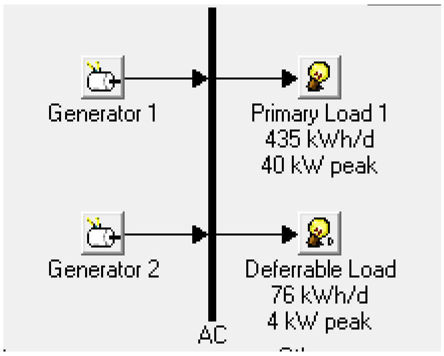


Figure 6. 22 Schematic of diesel only systems to supply the moderately constrained demand

Table 6. 19 System details with one diesel generator set to supply the moderately constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Diesel L/yr
89,083	1,146,118	7,343	0.48	71,401

Table 6. 20 System details with two diesel generators to supply the moderately constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Diesel L/yr
81,888	1,058,987	12,179	0.444	64,821

6.14.2.2 Diesel-Battery Systems

Figure 6.23 shows the system schematics and Table 6.21 and Table 6.22 give the details for one generator and two generator systems with a battery system, respectively.

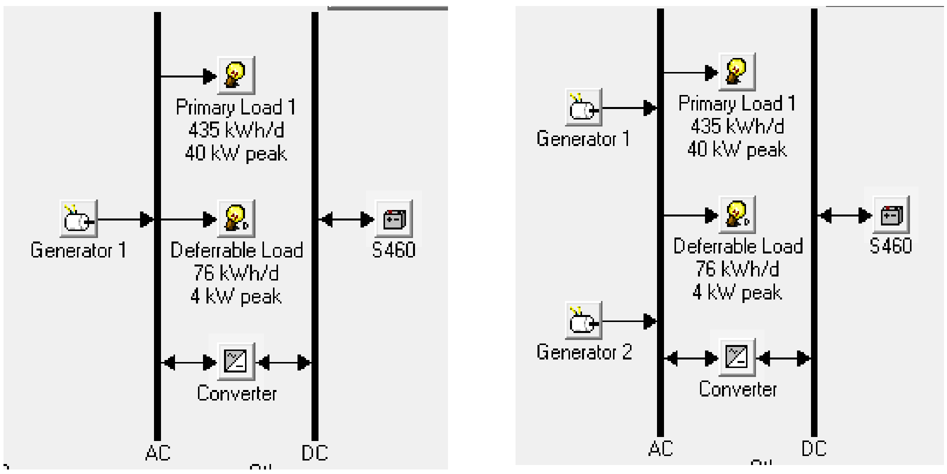


Figure 6. 23 Schematic of diesel-battery system to supply the moderately constrained demand

Table 6. 21 System details with one diesel generator and battery to supply the moderately constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Diesel L/yr
90,462	1,282,150	123,442	0.537	65,121

Table 6. 22 System details with two diesel generators and battery to supply the moderately constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Diesel L/yr
88,774	1,263,471	128,636	0.530	62,485

6.14.2.3 PV-Battery System

Figure 6.24 shows the system schematic and Table 6.23 gives the details of the system with solar PV and a battery bank to supply the moderately constrained demand.

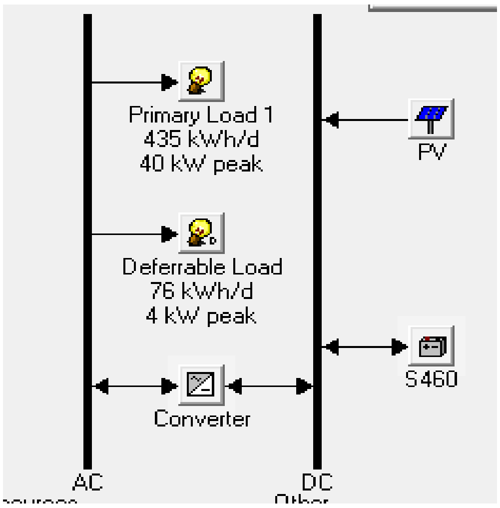


Figure 6. 24 Schematic of PV-battery system to supply the moderately constrained demand

Table 6. 23 System details with PV-battery to supply the moderately constrained load

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	PV size (kW)
35,750	1,550,625	1,093,615	0.650	1100	180

6.14.2.4 PV-Diesel-Battery System

Figure 6.25 shows the system schematic and Table 6.24 gives the details of the system with solar PV, a diesel generator and a battery bank to supply the moderately constrained demand.

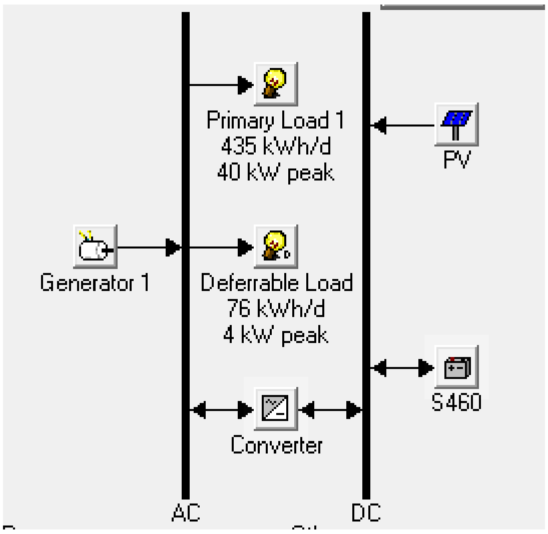


Figure 6. 25 Schematic of PV-diesel-battery system to supply the moderately constrained demand

Table 6. 24 System details with PV-diesel-battery to supply the moderately constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	PV (kW)	Diesel (L)	RE %
61,525	1,120,443	333,942	0.470	370	50	40,230	39

6.14.2.5 PV-Wind-Battery System

Figure 6.26 shows the system schematic and Table 6.25 gives the details of the system with solar PV, wind turbines and a battery bank to supply the moderately constrained demand.

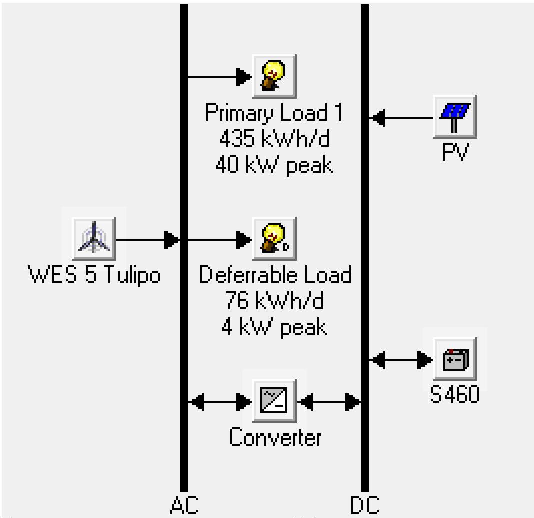


Figure 6. 26 Schematic of PV-wind-battery system to supply the moderately constrained demand

Table 6. 25 System details with PV-wind-battery to supply the moderately constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	PV (kW)	WT Nos.
24,923	1,161,964	843,365	0.487	560	105	26

6.14.2.6 Wind-Battery System

Figure 6.27 shows the system schematic and Table 6.26 gives the details of the system with wind turbines and a battery bank to supply the moderately constrained demand. With only wind turbines and battery storage, it was difficult to get a suitable configuration to meet 100% demand. The system components required were too high for the island environment. A feasible solution only results in at least 4% capacity shortage. The excess electricity generated was more than the primary energy requirements, which was 173,812 kWh per year with an annual unmet load of 6,521 kWh.

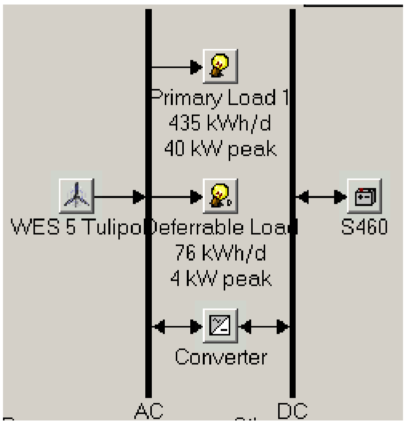


Figure 6. 27 Schematic of wind-battery system to supply the moderately constrained demand

Table 6. 26 System details with wind-battery to supply the moderately constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	WT Nos.	Shortage %
45,335	1,428,347	848,815	0.620	1340	50	4

6.14.2.7 Wind-Diesel-Battery System

This system operates with a diesel generator set of 25 kW burning 15,198 litres of diesel fuel oil annually and a renewable energy contribution of 84 percent. Figure 6.28 shows the system schematic and Table 6.27 gives the details of the system with wind turbines, diesel generators and a battery bank to supply the moderately constrained demand.

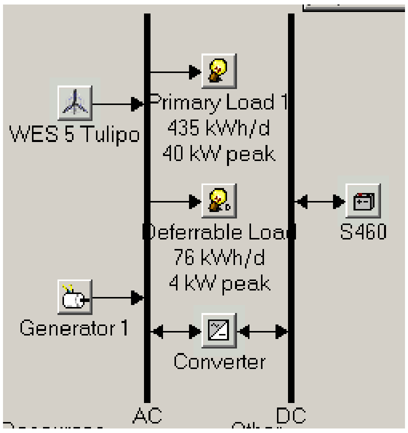


Figure 6. 28 Schematic of wind-diesel-battery system to supply the moderately constrained demand

Table 6. 27 System details with wind-diesel-battery to supply the moderately constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	WT Nos.	RE,%
32,026	795,343	385,942	0.333	370	30	84

6.14.2.8 Wind-PV–Diesel System

For this system configuration, the system does not use any PV for the system with lower NPC but the second system uses 1 kW of PV. Even with PV arrays neither COE nor renewable energy contribution displayed significant changes. Both systems consider a 35 kW diesel generator set and 20 wind turbines. Figure 6.29 shows the system schematic and Table 6.28 gives the details of the system with wind turbines, solar PV arrays and diesel generators to supply the moderately constrained demand.

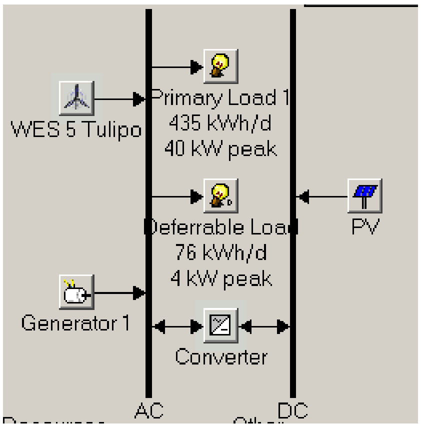


Figure 6. 29 Schematic of wind-PV-diesel system to supply the moderately constrained demand

Table 6. 28 System details with wind-PV-diesel to supply the moderately constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	PV(kW)	WT Nos.	RE,%
65,142	1,015,073	182,343	0.425	-	20	57

6.14.2.9 Wind-PV–Diesel–Battery system

Figure 6.30 shows the system schematic and Table 6.29 gives the details of the system with wind turbines, solar PV arrays, a diesel generator and a battery bank to supply the moderately constrained demand. PV arrays are not the first choice. As a second choice the system uses 4 kW of PV arrays and the number of wind turbines is reduced to 26 from 28 and the battery number remains the same; COE remains almost the same and RE falls by one percent.

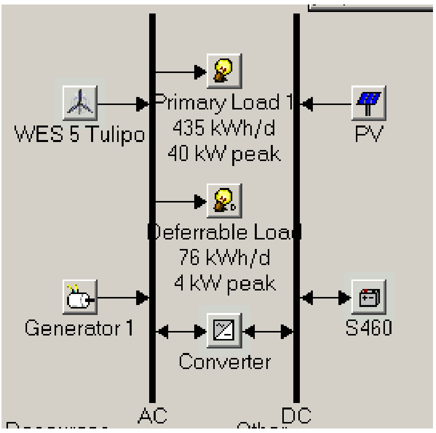


Figure 6. 30 Schematic of wind-PV-diesel-battery system to supply the moderately constrained demand

Table 6. 29 System details with wind-PV-diesel-battery to supply the moderately constrained demand.

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	PV(kW)	WT Nos.	RE,%
34,950	815,223	368,442	0.342	-	28	83

6.14.3 Results of the Supply Systems Modelled for the Severely Constrained Demand

Unlike with the systems for the present load, when modelling the systems for the severely constrained scenario no shortages were allowed as the load was considered essential for the well-being of the residents. Also unlike the present load systems, the deferrable loads were separated from the primary load. For a severely constrained load, deferrable peak loads of 2 kW and 4 kW were used as sensitivities.

6.14.3.1 Diesel Only Systems

Figure 6.31 shows the system schematics and Table 6.30 and Table 6.31 gives the details of the systems with one and two diesel generators to supply the severely constrained demand. The system with one generator uses a 35 kW unit and the system with two uses 20 kW and 12 kW units.

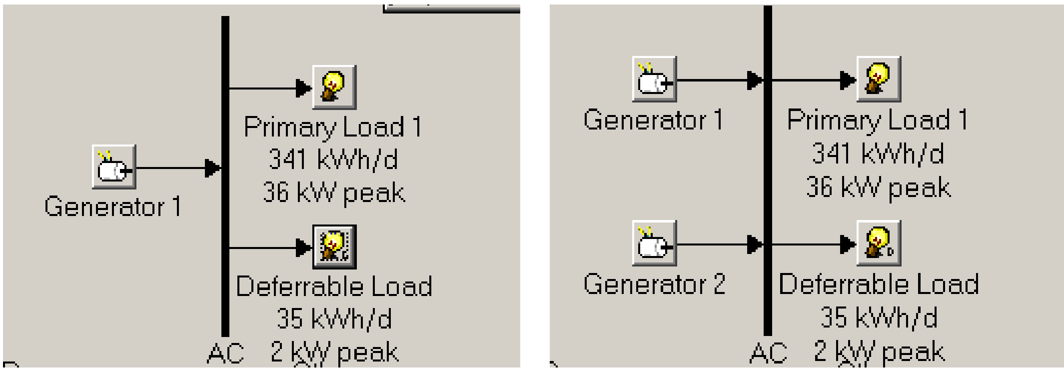


Figure 6. 31 Schematic of diesel only generators to supply the severely constrained demand

Table 6. 30 System details with diesel generators to supply the severely constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Diesel L/yr
73,238	943,356	7,128	0.538	58,270

Table 6. 31 System details with two diesel generators to supply the severely constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Diesel L/yr
62,900	816,037	11,964	0.465	48,849

6.14.3.2 Diesel with Battery Systems

Figure 6.32 shows the system schematics and Table 6.32 and Table 6.33 give the details of the systems with one and two diesel generators with battery banks to supply the severely constrained demand. The system with one generator uses a 20 kW unit whereas the system with two uses 16kW and 8 kW units. In both the cases a battery bank of 270 batteries were used.

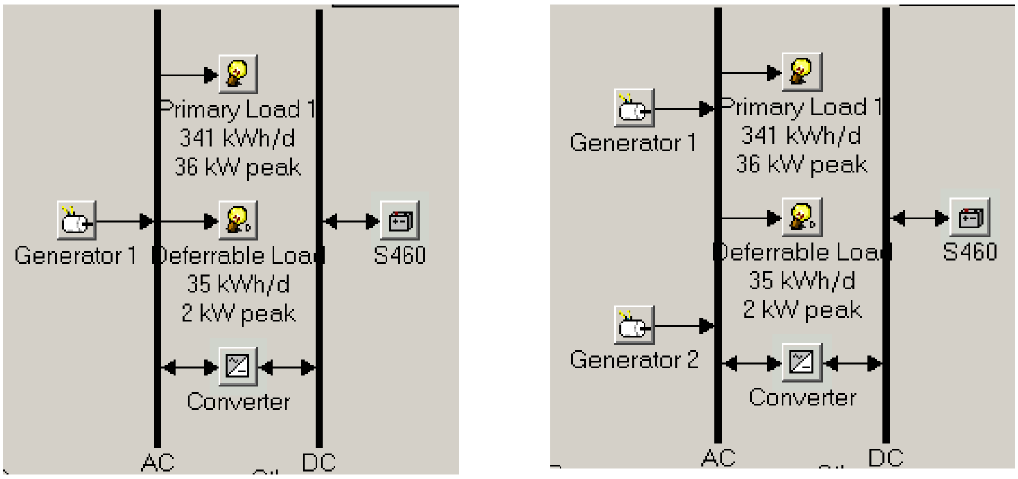


Figure 6. 32 Schematic of diesel-battery system to supply the severely constrained demand

Table 6. 32 System details with one diesel generator and battery for severely constrained demand

Operating cost/year($)	**NPC ($)**	**Initial Capital($)**	**COE ($/kWh)**	**Diesel L/yr**
67,811	958,773	91,917	0.547	48,635

Table 6. 33 System details with two diesel generators and battery for severely constrained demand

Operating cost/year($)	**NPC ($)**	**Initial Capital($)**	**COE ($/kWh)**	**Diesel L/yr**
66,891	952,126	97,039	0.543	46,628

6.14.3.3 PV and Battery Storage System

Figure 6.33 shows the system schematic and Table 6.34 gives the details of the system with solar PV and a battery bank to supply the severely constrained demand.

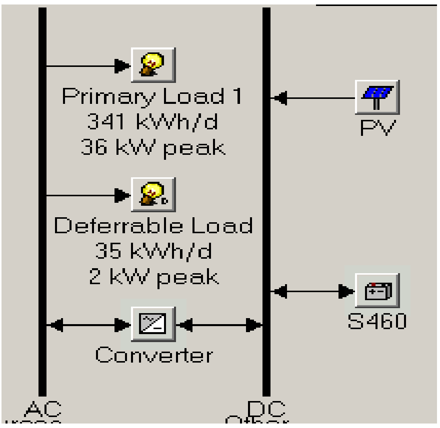


Figure 6. 33 Schematic of PV-battery system to supply the severely constrained demand

Table 6. 34 System details with PV-battery to supply the severely constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	PV size (kW)
26,671	1,177,999	837,048	0.672	810	140

6.14.3.4 PV-Diesel-Battery System

Figure 6.34 shows the system schematic and Table 6.35 gives the details of the system with solar PV, a diesel generator and a battery bank to supply the severely constrained demand.

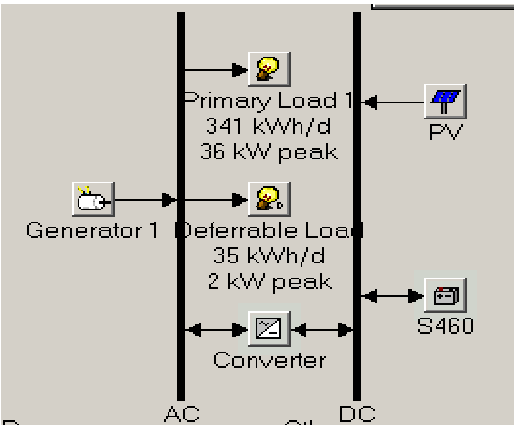


Figure 6. 34 Schematic of PV-diesel-battery system to supply the severely constrained demand

Table 6. 35 System details with PV-diesel-battery to supply the severely constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	PV (kW)	Diesel (L)	RE %
46,863	842,908	243,835	0.481	270	36	31,000	37

6.14.3.5 PV-Wind-Battery System

Figure 6.35 shows the system schematic and Table 6.36 gives the details of the system with solar PV, wind turbines and a battery bank to supply the severely constrained demand.

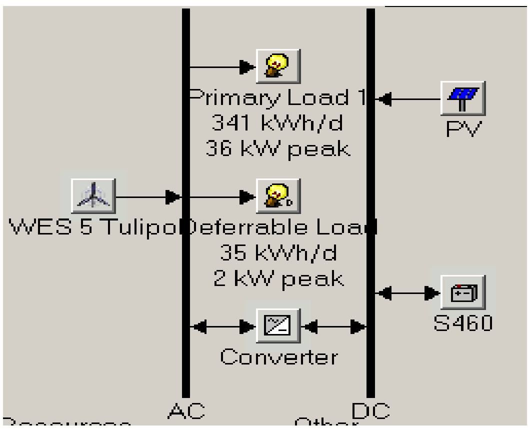


Figure 6. 35 Schematic of PV-wind-battery system to supply the severely constrained demand

Table 6. 36 System details with PV-wind-battery to supply the severely constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	PV (kW)	WT Nos.
18,633	884,194	645,998	0.505	420	85	18

6.14.3.6 Wind-Battery System

Figure 6.36 shows the system schematic and Table 6.37 gives the details of the system with wind turbines and a battery bank to supply the severely constrained demand. With only wind turbines and battery storage, it was difficult to get a suitable configuration to meet 100% demand. The system components required were too high for the island environment. A feasible solution is possible only with a 5% capacity shortage. The excess electricity generated was more than the primary energy requirement, which was 215,177 kWh per year with an annual unmet load of 5,365 kWh.

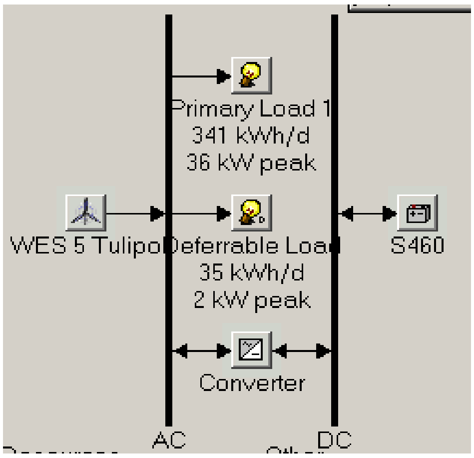


Figure 6. 36 Schematic of wind-battery system to supply the severely constrained demand

Table 6. 37 System details with wind-battery to supply the severely constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	WT Nos.	Shortage %
22,800	855,276	563,815	0.508	460	48	5

6.15.3.7 Wind-Diesel-Battery System

This system operates with a diesel generator set of 25 kW burning 12,012 litres of diesel fuel annually and a renewable energy contribution of 81 percent. Figure 6.37 shows the system schematic and Table 6.38 gives the details of the system with wind turbines, diesel generators and a battery bank to supply the severely constrained demand.

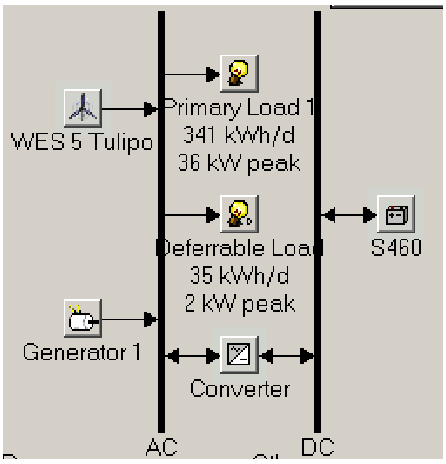


Figure 6. 37 Schematic of wind-diesel-battery system to supply the severely constrained demand

Table 6. 38 System details with wind-diesel-battery to supply the severely constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	Battery Nos.	WT Nos.	RE,%
27,982	645,977	288,275	0.368	340	20	81

6.14.3.8 Wind-PV-Diesel System

Figure 6.38 shows the system schematic and Table 6.39 gives the details of the system with wind turbines, solar PV arrays and diesel generators to supply the severely constrained demand. For this system configuration, the system does not use any PV for the system with lower NPC but the second system uses 20 kW of PV. Even with PV arrays COE has no significant changes but the renewable energy contribution increases to 57% from 52%. Both the systems use a 35 kW diesel generator set and 14 wind turbines for the first system and 12 wind turbines for the second system.

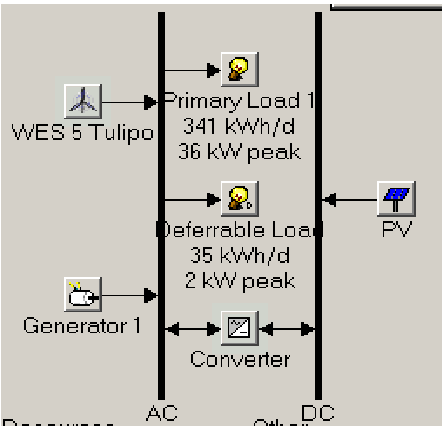


Figure 6. 38 Schematic of wind-PV-diesel system to supply the severely constrained demand

Table 6. 39 System details with wind-PV-diesel to supply the severely constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	PV(kW)	WT Nos.	RE,%
58,430	876,774	129,843	0.500	-	14	52

6.14.3.9 Wind-PV-Diesel-Battery System

The system does not consider PV arrays in the first choice but as a second choice the system considers 2 kW of PV arrays. With PV consideration there was no change to the number of wind turbines. Battery number remains same, COE remains the same and RE contribution increases by one percent. Figure 6.39 shows the system schematic and Table 6.40 gives the details of the system with wind turbines, solar PV arrays, a diesel generator and a battery bank to supply the severely constrained demand.

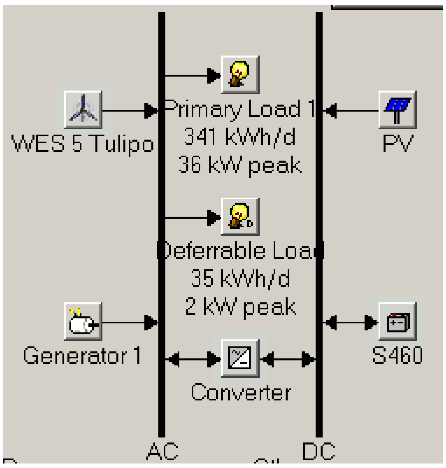


Figure 6. 39 Schematic of wind-PV-diesel-battery system to supply the severely constrained demand

Table 6. 40 System details with wind-PV-diesel-battery to supply the severely constrained demand

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	PV(kW)	WT Nos.	RE,%
28,428	647,155	283,775	0.369	-	20	81

6.14.4 The Final System Configuration Selected for the Island Community

Figure 6.40 is the schematic of the system with all generating sources and Table 6.41 shows the important technical details from the simulation. Figure 6.41 and Figure 6.42 show a cash flow summary of the life time costs of different components, as well as capital cost and the over time costs of different components. The final selected system shows that even with 30 percent power supply from diesel generators, the highest NPC is on diesel generation for a life of over 25 years. Figure 6.43 shows higher capital costs due to the high upfront cost of the renewable sources. Figure 6.44 shows the monthly average electric production from the three sources considered.

The final hybrid system chosen for the community has the minimum renewable energy sources to meet the essential load but uses diesel to supplement the present load. A variety of design parameters such as PV size, wind turbine sizes and numbers and battery capacity have been considered. The minimum renewable energy sources to supply the essential loads of the community were simulated with diesel generators to find the optimal supply mix for the present load. The final outcome has the following characteristics: NPC and COE were $1,532,340 and $0.37/kWh respectively, lower than any diesel-only systems that could supply the demand. The total annual electricity production is 386,444 units (kWh), of which 9.61% is excess electricity and the annual operating cost is $68,688. Compared to the diesel-only systems there is a fuel savings of 77,021 litres of diesel per year, which is a 66.5 %

reduction. An annual carbon dioxide emission reduction of 202,824 kg was achieved, which is a reduction of 66.5%. An annual renewable energy contribution of 70% would be achieved, 34% of which would be from PV arrays and 36% from wind turbines.

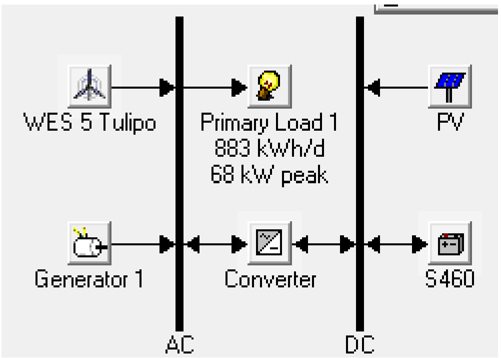


Figure 6. 40 Schematic of final system selected to supply the island community's electric demand

Table 6. 41 System details of the final configuration to supply the island's electric load

Operating cost/year($)	NPC ($)	Initial Capital($)	COE ($/kWh)	PV(kW)	WT Nos.	RE,%
68,688	1,532,340	654,283	0.372	85	18	70

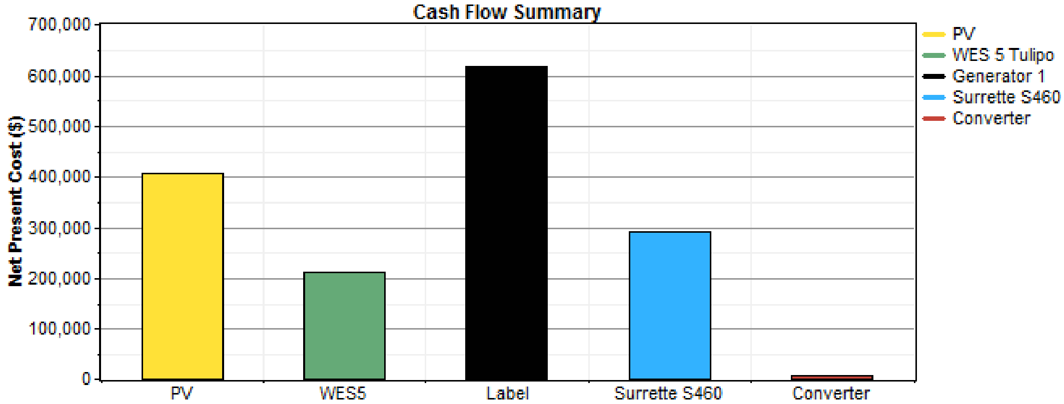


Figure 6. 41 Cash flow summary of the life time costs of different components in final selected system to supply the electric load

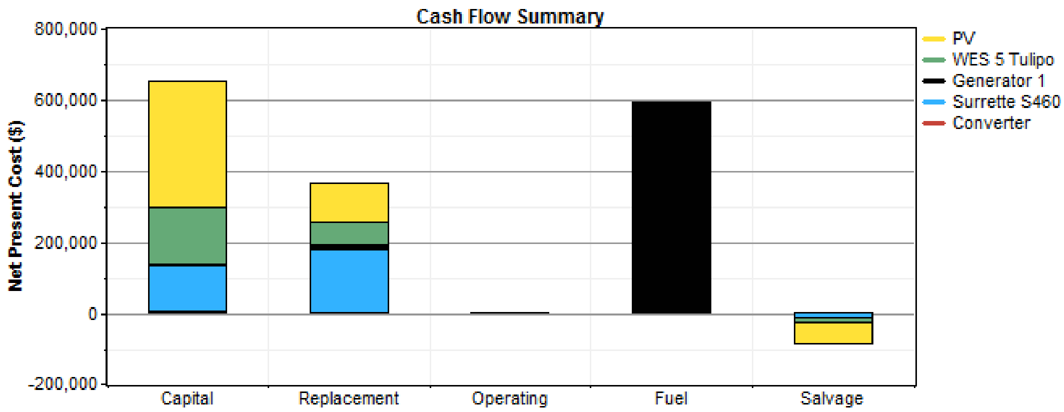


Figure 6. 42 Capital cost and over the time costs of different components of the final selected system to supply the electric load

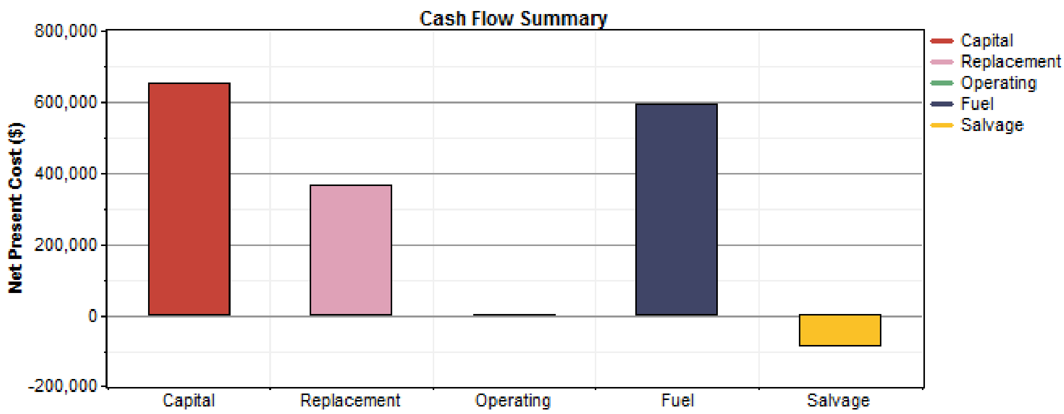


Figure 6. 43 Categorized life time costs of the final selected system to supply the electric load

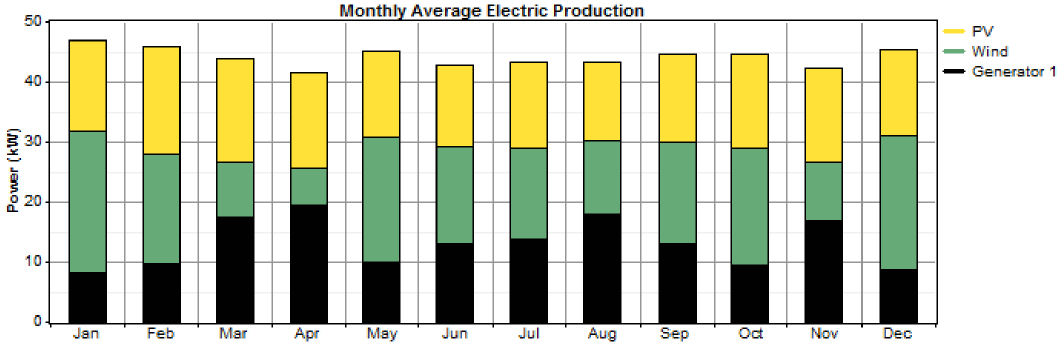


Figure 6. 44 Monthly average electric production from different sources of the system

Payback Period and Economic Comparision

In HOMER the payback period is calculated by comparing one system with another. In general, payback indicates the number of years it will take to recover an investment. Generally a certain amount of money is invested up front, then income is earned from that investment and payback is the number of years it takes for the cumulative income to equal the value of the initial investment.

In this case study the "income" of the selected power system is compared to a base case, which is the present generation system on the island. A distributed power system of this nature is usually not simple. A system must be designed to provide electricity in an off-grid situation. The existing pure diesel system has low initial investment (capital cost) and high operating costs, whereas the selected hybrid system has a higher initial investment and low operating cost. It is assumed neither system produces any income for the purpose of comparison. In both cases money is spent up front to build the system and money is spent each year to operate the system. In this way the concept of payback is meaningful—when two alternative systems are being compared. The payback of the additional investment required for the hybrid system is defined by comparing the difference in capital cost with the difference in operating cost. Hence, to calculate the payback period two alternatives are being compared. In this case a hybrid power generation system is being compared to a non-renewable conventional diesel power system (the base case). HOMER allows the choosing of any case from the simulations to act as a base for comparing any two systems of interest and to calculate the payback of the system desired. Figure 6.45 shows the details of the nominal and discounted payback period of the selected system compared to the existing generation system on the island.

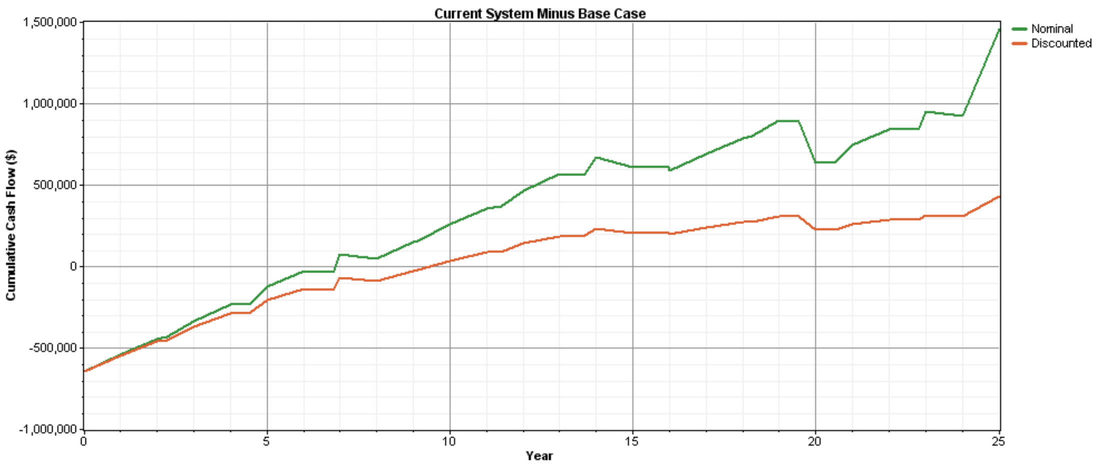


Figure 6. 45 Payback period of the selected hybrid system in reference to the existing power system

When the base case system is chosen, the metric table in the HOMER window shows economic measures representing the value of the difference between the two systems (Table 6.42):

Table 6. 42 Economic parameters of the selected system compared to present system

Metric	Value
Present worth	$ 432,761
Annual worth	$ 33,853/yr
Return on investment	13.1 %
Internal rate of return	13.0 %
Simple payback	6.89 yrs
Discounted payback	9.47 yrs

The **present worth** is the difference between the net present costs of the base case system and the hybrid system. A positive value indicates that the current system saves money over the project lifetime compared to the base case system. The **annual worth** is the present worth multiplied by the capital recovery factor (CRF). **Return on investment** (ROI) is calculated by subtracting the cumulative nominal cash flow in year zero from the cumulative nominal cash flow in the final year. Divide that number by the lifetime and then again by the cumulative nominal cash flow in year zero. Note that the cumulative nominal cash flow in year zero is equivalent to the base case capital cost minus the current system capital cost. The **internal rate of return** (IRR) is the discount rate at which the base case and current system have the same net present cost. HOMER calculates the IRR by determining the discount rate that makes the present value of the difference of the two cash flow sequences equal to zero. **Payback** is the number of years at which the cumulative cash flow of the difference between the current system and the base case system switches from negative to positive. The payback is an indication of how long it would take to recover the difference in investment costs between the current system and the base case system. **Simple payback** is where the nominal cash flow difference line crosses zero. **Discounted payback** is where the discounted cash flow difference line crosses zero.

Chapter 7

Generation Systems Assessment Criteria

Two basic assessment criteria are used for the analysis of the generation systems designed in this work. Namely the risk assessment of the supply systems and “a new approach to identifying the power supply system’s suitability”. The latter uses the important parameters from the HOMER analysis. In the following sections of this chapter these two criteria are explained.

7.1 Risk Assessment of Generation Systems

7.1.1 Introduction

The methodology used to account for the risks was briefly discussed in Chapter 3. In this study the risks considered are the risks to/from the electric power generation systems. The following categories are considered for each system:

- General feasibility,
- Resource security, and
- Environmental problems

All ranking scales used in this study contain five chance and consequence levels. These could additionally be categorised into three risk levels, namely low risk, medium risk and high risk. Different scales are being used for the impacts in different risk categories and are explained in the subsequent sections. The scale used for ranking likelihoods of occurrence (p) is the same for all categories, as described below in Table 7.1:

Table 7. 1 Ranks of likelihood of occurrences (p)

Likelihood of occurrence(p)	Ranking
Most unlikely	1
Rather unlikely	2
Equally likely and unlikely	3
Rather likely	4
Most likely	5

7.1.2 General Feasibility

The general feasibility of the electric power generation system describes a group of risks to the fundamental and technical realization of the energy system configuration concepts. Some of the important issues considered under general feasibility are:

Fundamental issues: problems created by the fundamental laws of science, such as the laws of thermodynamics.

Technical issues: describes technical problems in architecture, design and manufacture, or technical problems with system operation and controls.

Application issues: problems that may arise from integration into the existing technical and social system. These issues need a thorough investigation for successful implementation.

Cost issues: the most common concept obstacles. If systems are economically viable, the costs become part of the standard risk assessment.

Risks that arise from feasibility issues are evaluated according to their impacts on the functionality of the power supply system (using the following ranking in Table 7.2 on a scale from one to five to make it more consistent with the referenced concept diagram in Figure 3.2). Other rankings—from one to four—are often very common in the literature:

Table 7. 2 Impact rankings for feasibility issues

Description of impact (i)	**Ranking**
Minor energy system disturbances, e.g. minor power quality issues or brownouts	1
Minor energy system disruptions, e.g. short blackouts	2
Severe energy system disruptions, e.g. several days of blackouts, financial losses of up to 5% of investment, and/or permanent loss of 10 to 20% of energy services	3
Major energy system disruptions, e.g. several days of blackouts, financial losses up to 20% of investment, and/or permanent loss of 20 to 75% of energy services	4
Severe disruptions and system damage, e.g. several days of blackouts, financial losses of more than 20% of investment, and/or permanent loss of more than 75% of energy services	5

7.1.3 Resource Security

Resource security is evaluated by means of events with the potential to disrupt the power supply system. Resource security is not only limited to the energy resources used to run the power plants, but also involves the supply of system components and materials. As is the norm for power generation systems, the project lifetime is taken as 25 years, and the likelihood of events challenging resource security shall be the likelihood of these occurring within the project’s lifetime. Below possible events are described, with their potential for impairing resource security and the likelihood of these occurring within the project life:

Doubling of fuel prices, a 50% irreversible reduction in fossil fuel supply and as a consequence a 50% reduction of fuel supply trips to the island. The probability of this occurring within the next 25 years is considered most likely. A major natural disaster such as a tsunami striking the Maldives (Fenfushi island) within the project life is a rather unlikely event, but an event of a sustained winds of up to 50km/h are equally likely and unlikely. The likelihood of occurring extended periods of inter-tropical convergence with no power winds for a period of a month or more in any given year is set to low. The available wind data supports this assumption. The impacts of resource security risks are evaluated on the same scale as feasibility risks, as described in Table 7.2.

7.1.4 Environmental Damage

One increasingly important area of regulations with regard to the environment is risk. Fossil fuel fired power plants are a significant contributor to greenhouse gases, and these generation methods have come under increasing scrutiny from governments worldwide, especially in those countries who are signatories to Kyoto Protocol[3]. For some countries this agreement requires significant and costly (for the country's

[3] The Kyoto Protocol was the world's first international government agreement on reducing carbon dioxide emissions, signed initially in 1997. Essentially, the Kyoto Protocol deal requires most OECD countries to reduce their carbon emissions to close to 1990 levels.

economy) reductions in output from fossil fuel fired generation plants. The significant link between electricity generation and carbon dioxide emissions has caused many researchers to begin the analysis of future scenarios for restriction and reiteration of fossil fuel power generation plants.

The potential impacts of environmental damage are rated on the following scale (Table 7.3):

Table 7. 3 Impact rankings for environmental issues

Description of impact (i)	**Ranking**
Adversely affects well-being of present population	1
Adversely affects well-being, minor short term health effects on population or minor decline in essential resources	2
Significant short term health effects or minor long term health effects, or significant decline in essential resources	3
Major long term health effects or major decline of essential resources, or some premature deaths	4
Major long term health effects or major decline of essential resources, causing many premature deaths or island becoming uninhabitable	5

7.1.5 Individual System Risk Assessment Criteria

This section summarises all the risks that have been identified for any power supply system configurations studied for power generation on Fenfushi Island. Some risks apply to most systems; others only apply to single system concepts. General risks are listed in Table 7.4 and specific configuration concept risks for resource security and environmental problems are listed in Tables 7.5 and 7.6, respectively.

Table 7. 4 System risk assessment criteria for general feasibility

Risk description	**Evaluation criteria**
Fundamental issues	
Premature turbine failure due to corrosion in marine environment	P *f*(total exposed equipment, durability), durability assumed to be higher for large commercial turbines. i Set to “3” for all systems
Premature PV panel failure due to corrosive marine environment	P *f*(total exposed solar PV areas) i Set to “3” for all systems
Technical issues	
Power quality problems due to high renewable energy (wind/PV) penetration	P *f*(system capacity); a higher capacity system is assumed to have better power electronics to mitigate quality problems. i Set to “1” for all systems
Problem of space limitations for wind turbines	P *f*(number of wind turbines) i set for 1
Problem of space limitations for PV panel installations	P *f*(PV capacity, kW) i set for 1
Application issues	
Repair delays due to long turnaround times	P *f*(access to island and availability of technical personnel) i *f*(energy system complexity); a complex system with many components and power electronics means professional plant operators.
Damage to plant due to improper use	P *f*(plant robustness) i Set to “3” for all systems
Cost issues	
Continuous financing problems	P *f*(cost of electricity, unit cost , total household bill.). i Set to “4” for all systems
Difficulties in finding the capital investment	P *f*(initial investment) i Set to “5” for all systems

Table 7. 5 System risk assessment criteria for resource security

Risk description	**Evaluation criteria**
Resource security System disruptions by 50% reduction in petroleum imports to the country	P set to "5" for all systems; i.e. the likelihood of peak oil occurrence within project life. i *f*(petroleum (diesel) fuel use, system flexibility)
Plant repair/operation difficulties due to 50% reduction of access trips to the island due to peak oil	P *f*(no. of fuel trips to the island and frequency of plant failures) i *f*(energy system complexity)
Damage to plant due to natural disasters	P set to "1" for all systems; i.e. the likelihood of a disaster occurring within project life i *f*(robustness of exposed equipment)
Wind resource problems due to calm periods in a year	P Set to "2" for all systems; i.e. the estimated likelihood of calm periods i *f*(system flexibility, storage capacity)
Solar resource problems due to cloudy periods of no sun	P set to "2" for all systems; i.e. the likelihood of extended low sunshine periods i *f*(system flexibility, storage capacity)

Table 7. 6 System risk assessment criteria for environmental problems

Risk description	**Evaluation criteria**
Environmental problems	
Accumulation of old machinery, excluding batteries	P *f*(required amount of equipment) i *f*(toxicity and space accumulation)
Large scale contamination of soil/groundwater by waste engine oil	P *f*(system capacities, system dispersion); smaller distributed systems are assumed to cause relatively more problems i Set to “3” for all systems
Soil/groundwater contamination due to petroleum fuel spills on land	P *f*(system capacities, system dispersion); smaller distributed systems are assumed cause relatively more problems i Set to “3” for all systems
Sea contamination due to petroleum fuel spills during delivery	P *f*(no. of fuel trips, total diesel Fuel requirements) i set to “5” for all systems
Local air pollution due to engine exhausts	P *f*(no. of people living near generators); higher for distributed generators than central systems i *f*(system capacity)
Noise pollution due to plant operation	P *f*(type and size of equipment, plant disparity); distributed systems affect a greater no. of people i set to “1”for all systems
Habitat destruction due to land requirements	P *f*(plant space requirements) i set to “3” for all systems
Soil/groundwater contamination due to battery spillages	P *f*(no. of required batteries, plant dispersion, service level); distributed systems cause greater problems; higher service level is assumed to mean professional operators and thus more appropriate handling i set to “3” for all systems
Soil/groundwater contamination due to battery dumping	P *f*(no. of required batteries, plant dispersion, service level); distributed systems cause greater problems; higher service level is assumed to mean professional operators and thus more appropriate handling i set to “3” for all systems

Decimation of bird populations due to large wind turbines	p *f*(no. and rotor diameter of turbines) i set to “2” for all systems
Soil/groundwater contamination through accumulation of old appliance rubbish	P *f*(no. of appliances); a higher service level is assumed to incur more appropriate rubbish disposal i *f*(No. of appliances)

The likelihood of both PV and wind systems existing together is based on the number of individual system components as set in Table 7.7 and Table 7.8. The capacity limitations for PV panel installations are set based on the suitable available area on the island. The number of wind turbines that could be used on the island are limited as the area considered for the wind turbine is on the western part of the island where no households exist. It is considered a suitable place due to the landscape and wind profile of the region.

Table 7. 7 Ranks of likelihood (p) of occurrences of PV systems based on kW capacity

PV capacity (kW)	Ranking (likelihood)
1 – 20	1
21 – 40	2
41 – 60	3
61 – 80	4
81 – 100	5

Table 7. 8 Ranks of likelihood of occurrences of wind turbines

Number of turbines	Ranking (likelihood)
1 – 5	1
6 – 10	2
11 – 15	3
16 – 20	4
21 – 30	5

The likelihood of financing problems is mainly based on the cost of energy production, which is set according to the values shown in Table 7.9. The likelihood of initial investment problems is based on the initial capital requirements for the system, as shown in Table 7.10.

Table 7. 9 Ranks of likelihood of occurrences of continuous financing problems

Cost of Energy(COE),$/kWh	Ranking(likelihood)
COE< 0.4	1
0.4 < COE <0.5	2
0.5 < COE <0.6	3
0.6 < COE <0.7	4
0.7 < COE <0.9	5

Table 7. 10 Ranks of likelihood of occurrences of initial investment

Initial Investment(II),(US$)	Ranking(likelihood)
II< 100,000	1
100,000 < II < 300,000	2
300,000 < II < 500,000	3
500,000 < II < 600,000	4
600,000 < II < 800,000	5

7.1.6 Risk Results

The risk results for the electric power generation systems for the three load curves that were modelled in the previous chapter will be presented here. The system details are not discussed in this chapter, as they were discussed in Chapter 6. To simplify the findings, mostly the risk values are presented in this chapter. The risk for each component of the generation system is calculated according to the size of the components of the chosen system from the HOMER simulations and according to the criteria set in tables in Section 7.2. When two systems with one diesel generator and one with two diesel generators were modelled for the same load curve a common set of risks were calculated. From a risk analysis point of view the two systems are not different—they are made up of similar components.

There is a considerable difference between the energy supply systems in the magnitude and nature of their associated risks. It is this difference that allows us a degree of choice with regard to selecting energy systems that are most suitable to the location of interest. Because of all the uncertainties and risks associated with different energy systems, the decision makers must be familiar with the basics of risk analysis and be able to distinguish between issues of fact and value issues. As diversity provides a level of security against unforeseen risks, it is proposed that a system rely on more than one form of energy in the generation mix.

Table 7.11 shows a summary of the risks calculated for each of the nine power supply systems modelled for the three loads. The chosen supply system, which has minimum renewable energy sources and has the capacity to supply the required electric load in a severely constrained load situation (with supplementary diesel), has a total risk of 168. The system has a higher risk value as it is made up of all the potential generation components considered in this study and each contributes some level of risk. From an electricity supply security point of view this system has a higher standing as it is capable of providing the service despite the changes in the fuel market and other vulnerable situations. For a complete system analysis report see Appendix C.

Table 7. 11 Summary of risks calculated for the power generation systems modelled for the three loads.

	Load 1	**Load 2**	**Load 3**
Diesel only	83	89	105
Diesel + Battery	116	120	122
PV + Battery	∞	∞	∞
PV + Diesel + Battery	152	132	133
PV + Wind + Battery	∞	∞	138
Wind + Battery	∞	∞	∞
Wind + Diesel + Battery	133	116	122
Wind + PV + Diesel	∞	146	111
Wind + PV + Diesel + Battery	149	145	131

Note: Load 1: Present unconstrained load of the island

Load 2: Moderately constrained load

Load 3: Severely constrained load

For the selected system the calculated risk is 168.

All the risk values calculated are for the three set loads without any shortages in the supply system. For the present load with allowed shortages the values would be slightly lower but not significantly.

The risk values calculated for the power generation systems do not explicitly indicate that the higher the number the riskier the system is, rather in the context of this study the higher values result as a consequence of more power generating and control equipment associated with the system. Any value not indicated by infinity means the power generation system designed cannot be totally rejected; it is a feasible system but the individual system component risks need to be analysed. Rating the risks in such a way gives the stakeholders a very good indication of the possible individual component risks to the system.

7.2 A New Approach to Identifying the Power Supply System's Suitability

7.2.1 Introduction

One of the main limitations of the HOMER simulations is the way optimization is carried out. It is based on only one parameter, the NPC, and omits all the other results provided by the simulation (such as the renewable energy component or the diesel consumption). However, it is only possible to consider the systems in a specific range of values for the annual capacity shortage and renewable component. It is impossible to modify the way HOMER carries out optimization without changing the code of the software, so a new tool is introduced to compare the different simulated supply systems. This tool provides a new parameter, calculated using the results that affect the final decision making. The aim of this is to bring out the best systems and to quickly eliminate unfeasible systems. This criterion will be called Λ; it is fixed that the lower its value is, the better the system fits to the studied case. Different parameters can intervene in the formula, depending on the characteristics of the situation. In any case, one of the most important factors of the decision is clearly the cost of the supply system. But in this case the renewable energy component, which ensures energy independence, is treated as highly important as well. So the parameters will be balanced to ascertain the degree of importance. The proposed expression is as below:

$$\Lambda = \left(\frac{COE_{simulation}}{COE_{actual}}\right)^3 . \frac{1}{Renewable\ fraction} . \frac{1}{1 - Shortage\ fraction} . Diesel\ fraction$$

This equation considers ‘good’ and ‘bad’ supply system components—or in other words, favourable and unfavourable components. The good ones are supposed to reduce the value of Λ and the bad ones increase this value. This equation could only be used for hybrid systems, not for 100% renewable or only diesel based systems, for which new equations will be used. Even if the NPC of the system is more significant than the COE, due to the excess energy production, the actual NPC is really difficult to estimate, whereas the COE of the actual system is easily comprehensible. Therefore, if the COE of the simulation is higher than the actual present system that is used as a reference, the fraction will be superior to 1, and hence will increase the final value; if it is the inverse, Λ will decrease. This fraction of COE is balanced by a cube power to give a higher weight, which is the most important parameter in the expression.

The renewable fraction and the diesel fraction allow evaluation of the energy self-reliance. These two parameters are complementary and very similar, even if they do not represent the same thing, which is why each is just balanced with a power of 1.
The last parameter is more for the comfort of the community; the aim of the hybrid system is to supply the electric power consumption at a low cost while insuring energy security, so it is better to minimize the shortage time (load shedding).

Other formulas have been proposed for the 100% renewable and 100% diesel systems.
For 100% renewable systems:

$$\Lambda = \left(\frac{COE_{simulation}}{COE_{actual}}\right)^3 . \left(\frac{1}{Renewable\ fraction}\right)^2 . \frac{1}{1 - Shortage\ fraction}$$

For 0% renewable systems:

$$\Lambda = \left(\frac{COE_{simulation}}{COE_{actual}}\right)^3 . \frac{1}{1 - Shortage\ fraction} . (Diesel\ fraction)^2$$

The results obtained with these equations will give an idea of the range of the systems, but are not really comparable with the previous formula.

7.2.2 Λ Results

For the optimal system of each configuration, the Λ factor has been calculated. These results are in agreement with the previous analysis, so it is possible to classify the systems much more quickly using these results than by looking at each parameter of each system. Once the best configurations and designs have been identified, a final, thorough analysis is necessary to ensure that there are no mistakes made in carrying out the procedure.

The double analysis allows for the choosing of the most appropriate systems for power generation. The Λ results give a quicker insight into the generation system and save a substantial amount of time by avoiding detail analysis of infeasible systems. Table 7.12 gives a quicker classification of the generation systems based on the **Λ** value.

Table 7. 12 Classification of Λ

Λ Range	**System classification**
Λ<0.5	Excellent
0.5< Λ<1	Very good
1< Λ<5	Interesting
5< Λ<15	Needs improvement
15< Λ	Not worth considering

Table 7.13 gives the calculated values of the new parameter for the twenty seven supply systems studied in Chapter 6 for the three loads. The three equations

described in Section 7.2.1 have been used to calculate the values according to the composition of the generation system components.

Table 7.13 shows the calculated system suitability values for the three loads for the minimum NPC system in each system configuration simulated. The value is very sensitive to the COE ratio, as it is given a cubic power. The final selected system with minimum renewable energy components has a value of 0.48. With an incremental increase in the diesel fuel price the value further decreases, just as the COE of the present system would increase (this is used as a bench mark).

Table 7. 13 Summary of Λ values calculated for the lowest NPC power generation systems in each category modelled for the three loads.

	Load 1	**Load 2**	**Load 3**
Diesel only	1.34	1.32	1.51
Diesel + Battery	1.25	2.28	2.41
PV + Battery	12.88	13.08	14.81
PV + Diesel + Battery	4.76	4.29	5.38
PV + Wind + Battery	6.27	6.30	6.83
Wind + Battery	33.04	-	-
Wind + Diesel + Battery	0.79	0.20	0.53
Wind + PV + Diesel	6.55	1.67	2.98
Wind + PV+ Diesel + Battery	0.79	0.33	0.61

Chapter 8

Conclusions and Future Work

8.1 Conclusions

It is evident from the results that integration of renewable energy is feasible on these small islands. Considering what has been experienced in the past with regards to international conflicts and price variations, it is essential to have a minimum level of renewable electric energy integrated into the system to avoid loss of essential loads that directly affect the residents' quality of life. During the first Gulf war (1991), due to the risk of fuel supply interruptions it was common to have regular planned load shedding from different parts of the main islands and for remote and small islands it was common to limit the number of hours of electric power supply. On some islands the electricity was only provided (from diesel generators) from 6 pm to midnight.

When renewable energy sources are integrated into the present generation system—which could supply the essential loads (as seen in the load curve generated from by the survey)—then the risk of the total collapse of electric power system is eliminated. Even during the type of situations mentioned before, the most important electric energy uses would still be fulfilled.

Even though the cost of power generation from PV is higher than wind, it is still important to have some level of PV in the system for energy security reasons. The level of solar irradiation is very high in all parts of the Maldives and this makes it justifiable to incorporate a fair amount of electric power from PV. From the weather data of the country it is evident that throughout the year the availability of sunshine (hours of sunshine) is very high and this makes it more attractive in conjunction with battery storage. Supply shortages are introduced for the present level of demand in simulations. Significant amounts of the electric energy being used at present are not considered essential. With this allowance in most of the power generation systems, the NPC and the COE of the systems would fall significantly.

The methodology followed to find the minimum level of renewable energy integration into the system is a novel approach. It aims to find the appropriate level of renewable energy to be integrated into the power generation system of these islands based on the demand type and pattern. This could be considered the initial stages of transition to sustainable electrical energy (a transition from unsustainable, conventional diesel generation systems). Since it is going to be a constrained fossil fuel supply in the future for reasons mentioned in this thesis, the constrained scenarios from the conventional sources shows that the majority of people on these islands could go back to a somewhat similar situation in terms of energy use for domestic purposes and still continue a happy life.

Applying the methodology discussed in this thesis to finding the appropriate level of demand that strictly needs to be the generation capacity from the renewable sources would bring energy security to these islands. For domestic power uses, knowing that there exists a supply that will meet the required demand would psychologically give peace of mind and avoids getting panicked in likely situations of supply interruptions of diesel fuel oil. Applying the methodology to find the levels of Essential load or Necessary load for some islands, it is possible to ascertain (with the risk analysis of the supply systems as carried out in Chapter 7) that there is no suitable renewable energy system that could be implemented on some of islands due to their population size and available space for renewable energy system components. Nonetheless, the methodology developed in this thesis will help to identify the minimum electrical energy requirements for the wellbeing of the residents of the community and all the possible supply systems and risks posed to the system. Applying the methodology, islands and regions with possible severe risks in the future would be identified and the system's suitability factor could be used during the design phase to identify generation systems that are suitable without further time consuming analysis.

The selected electric power generation system for the island community following the steps of the proposed methodology is a hybrid system. A variety of design parameters such as PV size, wind turbine sizes and numbers and battery capacity have been considered. The minimum renewable energy sources to supply the essential loads of the community were simulated with diesel generators to find the optimal supply mix for the present load. The final outcome has the following characteristics: NPC and COE were $1,532,340 and $0.37/kWh respectively, lower than any diesel-only systems that could supply the demand. The total annual electricity production is 386,444 units (kWh), of which 9.61% is excess electricity and the annual operating cost is $68,688. Compared to the diesel-only systems there is a fuel savings of 77,021 litres of diesel per year, which is a 66.5 % reduction. An annual carbon dioxide emission reduction of 202,824 kg was achieved, which is a reduction of 66.5%. An annual renewable energy contribution of 70% would be achieved, 34% of which would be from PV arrays and 36% from wind turbines. The selected system shows that even with 30 percent power supply from diesel generators, still the highest NPC is on diesel generation for a life of over 25 years.

In this thesis a new methodology was developed to account for the minimum sustainable electric power supply system for remote island communities using renewable energy sources; this was demonstrated by means of a relatively simple case study. The method applied is generally applicable to any region in the world, not limited to the remote islands of the Maldives where the case study community was chosen. However, further research into the methodological framework of application to complex and wider regional systems with different characteristic loads is required to study the variations in the outcome results.

8.2 Future Work

In this thesis, a new methodology was developed to account for the minimum sustainable electric power supply system for remote island communities using renewable energy sources; this was demonstrated by means of a relatively simple case study. The method applied is generally applicable to any region; further research into the methodological framework of application to complex and wider regional applications is required—to entire atolls or two or more atolls treated as a common region.

The method used can be employed to identify sustainable regional electric power systems. Further research needs be directed towards its technical and also social implementation. In more complex regional systems, the risk analysis should be carried out by experts in those particular areas, such as environmental experts and energy system experts. This will help identify all possible risk events and their possible impacts. The methodology developed in this thesis could be used to implement such a system on one of the islands in the Maldives for demonstrative purposes.

A technical demonstration to showcase a new power production system, advanced technology or significant cost details is important to gather the support for this kind of projects. A demonstration would be able to provide necessary information to potential users, investors and decision-makers. The nature of the demonstrations of technologies and applications will ensure the long term benefits of a diverse mix of resources—both renewable and conventional—that can be realized using the available technologies. Successful implementation of any complex renewable technology will have a positive impact on future developments. On the other hand, projects or applications that are perceived as unsuccessful will have a negative impact on all future works of this nature.

References

Aalborg university, 'Department of Development and Planning,Advanced Energy System Analysis Computer Model,<http://energy.plan.aau.dk/>, accessed 19.05.2010'

Abdel-Aal, RE 2006, 'Modeling and forecasting electric daily peak loads using abductive networks', *International Journal of Electrical Power & Energy Systems*, vol. 28, no. 2, pp. 133-41.

Abdullah, MO, Yung, VC, Anyi, M, Othman, AK, Ab. Hamid, KB & Tarawe, J 2010, 'Review and comparison study of hybrid diesel/solar/hydro/fuel cell energy schemes for a rural ICT Telecenter', *Energy*, vol. 35, no. 2, pp. 639-46.

Ackermann, T (ed.) 2005, *Wind Power in Power Systems*, John Wiley & Sons, Ltd.

Ackermann, T, Andersson, G & Söder, L 2001, 'Distributed generation: a definition1', *Electric Power Systems Research*, vol. 57, no. 3, pp. 195-204.

Afgan, NH, Gobaisi, DA, Carvalho, MG & Cumo, M 1998, 'Sustainable energy development', *Renewable and Sustainable Energy Reviews*, vol. 2, no. 3, pp. 235-86.

Aftabuzzaman, M & Mazloumi, E 2011, 'Achieving sustainable urban transport mobility in post peak oil era', *Transport Policy*, vol. 18, no. 5, pp. 695-702.

Ai, B, Yang, H, Shen, H & Liao, X 2003, 'Computer-aided design of PV/wind hybrid system', *Renewable Energy*, vol. 28, no. 10, pp. 1491-512.

Al-Lawati, A, Dorvlo, A & Jervase, J 2003, 'Monthly average daily solar radiation and clearness index contour maps over Oman', *Energy Conversion and Management,* vol. 44, no. 5, pp. 691-705.

Alam Hossain Mondal, M, Kamp, LM & Pachova, NI 2010, 'Drivers, barriers, and strategies for implementation of renewable energy technologies in rural areas in Bangladesh--An innovation system analysis', *Energy policy,* vol. 38, no. 8, pp. 4626-34.

Alberg Østergaard, P, 'Transmission-grid requirements with scattered and fluctuating renewable electricity-sources', *Applied Energy,* vol. 76, no. 1-3, pp. 247-55.

Aleklett, K, Höök, M, Jakobsson, K, Lardelli, M, Snowden, S & Söderbergh, B 2010, 'The Peak of the Oil Age - Analyzing the world oil production Reference Scenario in World Energy Outlook 2008', *Energy policy,* vol. 38, no. 3, pp. 1398-414.

Almorox, J & Hontoria, C 2004, 'Global solar radiation estimation using sunshine duration in Spain', *Energy Conversion and Management,* vol. 45, no. 9-10, pp. 1529-35.

AlQdah, K 2010, 'Potential opportunities for energy savings in a Jordanian poultry company', *Energy Conversion and Management,* vol. 51, no. 8, pp. 1651-5.

Amjady, N & Daraeepour, A 2009, 'Mixed price and load forecasting of electricity markets by a new iterative prediction method', *Electric Power Systems Research,* vol. 79, no. 9, pp. 1329-36.

Andersen, AN & Lund, H 2007, 'New CHP partnerships offering balancing of fluctuating renewable electricity productions', *Journal of Cleaner Production,* vol. 15, no. 3, pp. 288-93.

Ardehali, MM 2006, 'Rural energy development in Iran: Non-renewable and renewable resources', *Renewable Energy,* vol. 31, no. 5, pp. 655-62.

Armenakis, A 2010, 'Bidirectional impact between distributed RES and small island grids', IEEE, pp. 148-53

Ashok, S 2007, 'Optimised model for community-based hybrid energy system', *Renewable Energy,* vol. 32, no. 7, pp. 1155-64.

Atkins, MJ, Morrison, AS & Walmsley, MRW 2010, 'Carbon Emissions Pinch Analysis (CEPA) for emissions reduction in the New Zealand electricity sector', *Applied Energy,* vol. 87, no. 3, pp. 982-7.

Aydinalp-Koksal, M & Ugursal, VI 2008, 'Comparison of neural network, conditional demand analysis, and engineering approaches for modeling end-use energy consumption in the residential sector', *Applied Energy,* vol. 85, no. 4, pp. 271-96.

Azadeh, A & Faiz, ZS 2011, 'A meta-heuristic framework for forecasting household electricity consumption', *Applied Soft Computing*, vol. 11, no. 1, pp. 614-20.

Azzaro-Pantel, C, Gourdon, C, Joulia, X, Lann, J-ML, Astier, S, Fontes, G, David, M & Ayache, A 2008, 'Development of sustainable energy systems: a new challenge for process systems engineering education', in B Bertrand & J Xavier (eds), *Computer Aided Chemical Engineering*, vol. Volume 25, Elsevier, pp. 1167-73.

Bakos, GC, Soursos, M & Tsagas, NF 2003, 'Technoeconomic assessment of a building-integrated PV system for electrical energy saving in residential sector', *Energy and Buildings*, vol. 35, no. 8, pp. 757-62.

Baring-Gould, E, Flowers, L, Lundsager, P, Mott, L, Shirazi, M & Zimmerman, J 2003, 'Worldwide Status of Wind-Diesel applications'

Barker, P, De Mello, R, Inc, P & Schenectady, N 2000, 'Determining the impact of distributed generation on power systems. I. Radial distribution systems', pp. 1645-56

Barton, J & Gammon, R 2010, 'The production of hydrogen fuel from renewable sources and its role in grid operations', *Journal of Power Sources*, vol. 195, no. 24, pp. 8222-35.

Battaglini, A, Lilliestam, J, Haas, A & Patt, A 2009, 'Development of SuperSmart Grids for a more efficient utilisation of electricity from renewable sources', *Journal of Cleaner Production*, vol. 17, no. 10, pp. 911-8.

Batty, WJ & Probert, SD 1989, 'Benefits of energy monitoring and auditing in the catering industry', *Applied Energy*, vol. 34, no. 3, pp. 193-211.

Bayón, L, Suárez, P, Matías, JM & Taboada, J 2009, 'Influence of forecasting electricity prices in the optimization of complex hydrothermal systems', *Journal of Computational and Applied Mathematics*, vol. 232, no. 2, pp. 262-74.

Bedford, T & Cooke, RM 2001, *Probabilistic risk analysis: foundations and methods*, Cambridge Univ Pr.

Bekele, G & Palm, B 2009, 'Wind energy potential assessment at four typical locations in Ethiopia', *Applied Energy*, vol. 86, no. 3, pp. 388-96.

Bentley, R, Mannan, S & Wheeler, S 2007, 'Assessing the date of the global oil peak: The need to use 2P reserves', *Energy Policy*, vol. 35, no. 12, pp. 6364-82.

Bhuiyan, M & Ali Asgar, M 2003, 'Sizing of a stand-alone photovoltaic power system at Dhaka', *Renewable Energy*, vol. 28, no. 6, pp. 929-38.

Biczel, P & Koniak, M 2011, 'Design of power plant capacity in DC hybrid system and microgrid', *COMPEL: Int J for Computation and Maths. in Electrical and Electronic Eng.,* vol. 30, no. 1, pp. 336-50.

Black, J 1956, 'The distribution of solar radiation over the earth's surface', *Theoretical and Applied Climatology*, vol. 7, no. 2, pp. 165-89.

Borbely, A & Kreider, J 2001, *Distributed generation: the power paradigm for the new millennium*, CRC.

Bray, M 1998, 'National self-determination and international dependence: the organisation and control of secondary school examinations in the small states of the Commonwealth', *Assessment in Education: Principles, Policy & Practice,* vol. 5, no. 2, pp. 151-73.

Brundtland, G & Khalid, M 1987, 'Our common future'

Campbell, C 2003, 'Industry Urged to Watch for Regular Oil Production Peaks', *Depletion Signals: Oil and Gas Journal*, pp. 38-45.

Campbell, C & Sivertsson, A 2003, 'Updating the depletion model'

Carew, AL & Mitchell, CA 2008, 'Teaching sustainability as a contested concept: capitalizing on variation in engineering educators' conceptions of environmental, social and economic sustainability', *Journal of Cleaner Production,* vol. 16, no. 1, pp. 105-15.

Catalão, JPS, Pousinho, HMI & Mendes, VMF 2011, 'Short-term electricity prices forecasting in a competitive market by a hybrid intelligent approach', *Energy Conversion and Management,* vol. 52, no. 2, pp. 1061-5.

Cavallo, A 2002, 'Predicting the peak in world oil production', *Natural Resources Research,* vol. 11, no. 3, pp. 187-95.

Celik, A 2004, 'A statistical analysis of wind power density based on the Weibull and Rayleigh models at the southern region of Turkey', *Renewable Energy,* vol. 29, no. 4, pp. 593-604.

Chaudhary, VP, Gangwar, B, Pandey, DK & Gangwar, KS 2009, 'Energy auditing of diversified rice-wheat cropping systems in Indo-gangetic plains', *Energy,* vol. 34, no. 9, pp. 1091-6.

Choudhuri, A & Gilman, P 1987, 'The influence of the Coriolis force on flux tubes rising through the solar convection zone', *The Astrophysical Journal,* vol. 316, pp. 788-800.

Clasen, T, Smith, L, Albert, J, Bastable, A & Fesselet, JF 2006, 'The drinking water response to the Indian Ocean tsunami, including the role of household water treatment', *Disaster Prevention and Management,* vol. 15, no. 1, pp. 190-201.

Connolly, D, Lund, H, Mathiesen, BV & Leahy, M, 'The first step towards a 100% renewable energy-system for Ireland', *Applied Energy*, vol. In Press, Corrected Proof

Connolly, D, Lund, H, Mathiesen, BV & Leahy, M 2010, 'A review of computer tools for analysing the integration of renewable energy into various energy systems', *Applied Energy*, vol. 87, no. 4, pp. 1059-82.

Contaldi, M, Gracceva, F & Tosato, G 2007, 'Evaluation of green-certificates policies using the MARKAL-MACRO-Italy model', *Energy Policy*, vol. 35, no. 2, pp. 797-808.

Crossley, P & Beviz, A 2010, 'Smart energy systems: Transitioning renewables onto the grid', *Renewable Energy Focus*, vol. 11, no. 5, pp. 54-6, 8-9.

Dalton, G, Lockington, D & Baldock, T 2009, 'Case study feasibility analysis of renewable energy supply options for small to medium-sized tourist accommodations', *Renewable Energy*, vol. 34, no. 4, pp. 1134-44.

de Almeida, A, Fonseca, P, Schlomann, B & Feilberg, N 2011, 'Characterization of the Household Electricity Consumption in the EU, Potential Energy Savings and Specific Policy Recommendations', *Energy and Buildings*, vol. In Press, Accepted Manuscript

De Vaus, D 2002, *Surveys in social research*, Routledge.

de Vries, B, Janssen, M & Beusen, A 1999, 'Perspectives on global energy futures: simulations with the TIME model', *Energy Policy*, vol. 27, no. 8, pp. 477-94.

Deffeyes, K 2001a, 'The End of Oil', *SCIENTIFIC AMERICAN*

Deffeyes, K 2001b, *Hubbert's peak*, Princeton University Press New Jersey.

Deshmukh, M & Deshmukh, S 2008a, 'Modeling of hybrid renewable energy systems', *Renewable and Sustainable Energy Reviews*, vol. 12, no. 1, pp. 235-49.

Deshmukh, MK & Deshmukh, SS 2008b, 'Modeling of hybrid renewable energy systems', *Renewable and Sustainable Energy Reviews*, vol. 12, no. 1, pp. 235-49.

Destatte, P 2010, 'Foresight: A major tool in tackling sustainable development', *Technological Forecasting and Social Change*, vol. 77, no. 9, pp. 1575-87.

Diamond, J 2006, *Collapse: How societies choose to fail or succeed*, Penguin Group USA.

Diamond, JM 2005, 'Collapse : how societies choose to fail or succeed '. Viking, New York.

Dincer, I 2000, 'Renewable energy and sustainable development: a crucial review', *Renewable and Sustainable Energy Reviews,* vol. 4, no. 2, pp. 157-75.

Dinica, V, Bressers, HTA & de Bruijn, T 2007, 'The implementation of a multi-annual agreement for energy efficiency in The Netherlands', *Energy policy,* vol. 35, no. 2, pp. 1196-212.

Diongue, AK, Guégan, D & Vignal, B 2009, 'Forecasting electricity spot market prices with a k-factor GIGARCH process', *Applied Energy,* vol. 86, no. 4, pp. 505-10.

Doukas, H, Nychtis, C & Psarras, J 2009, 'Assessing energy-saving measures in buildings through an intelligent decision support model', *Building and Environment,* vol. 44, no. 2, pp. 290-8.

Driesen, J & Belmans, R 2005, 'Distributed generation in future grids: Will "Energy Islands: become a reality', *Electric Power Quality and Utilisation Magazine,* vol. 1, no. 1, pp. 11-4.

Dufo-López, R & Bernal-Agustín, J 2005, 'Design and control strategies of PV-Diesel systems using genetic algorithms', *Solar Energy,* vol. 79, no. 1, pp. 33-46.

Dufo-Lopez, R, Bernal-Agustín, J & Contreras, J 2007, 'Optimization of control strategies for stand-alone renewable energy systems with hydrogen storage', *Renewable Energy,* vol. 32, no. 7, pp. 1102-26.

Dugan, R & Rizy, D 1984, 'Electric Distribution Protection Problems Associated with the Interconnection of small, disperesed Generation Devices', *IEEE Transactions on Power Apparatus and Systems*, pp. 1121-7.

Dugan, R, Thomas, S & Rizy, D 1984, 'Integrating dispersed storage and generation (DSG) with an automated distribution system', *IEEE Transactions on Power Apparatus and Systems,* pp. 1142-6.

Duic, N & da Graça Carvalho, M 2004, 'Increasing renewable energy sources in island energy supply: case study Porto Santo', *Renewable and Sustainable Energy Reviews,* vol. 8, no. 4, pp. 383-99.

Duic, N, Krajacic, G & da Graça Carvalho, M 2008, 'RenewIslands methodology for sustainable energy and resource planning for islands', *Renewable and Sustainable Energy Reviews*, vol. 12, no. 4, pp. 1032-62.

Duncan, R & Youngquist, W 1999, 'Encircling the peak of world oil production', *Natural Resources Research,* vol. 8, no. 3, pp. 219-32.

Edwards, A 1989, 'The Implications of Sea Level Rise for the Republic of Maldives', *Commonwealth Secretariat*

El-Hefnawi, SH 1998, 'Photovoltaic diesel-generator hybrid power system sizing', *Renewable Energy*, vol. 13, no. 1, pp. 33-40.

El-Shimy, M 2009, 'Viability analysis of PV power plants in Egypt', *Renewable Energy*, vol. 34, no. 10, pp. 2187-96.

Elagib, N, Babiker, S & Alvi, S 1998, 'New empirical models for global solar radiation over Bahrain', *Energy Conversion and Management*, vol. 39, no. 8, pp. 827-35.

Elkington, J 1997, 'Cannibals with Forks: The Triple Bottom Line of Twenty First Century Business', *Capstone, Mankato, MN*

Elliott, D, Schwartz, M, Scott, G, Haymes, S, Heimiller, D & George, R 2003, *Wind energy resource atlas of Sri Lanka and the Maldives*, National Renewable Energy Laboratory (NREL), Golden, CO.

EMD International A/S, *<http://www.emd.dk/>,accessed 19.05.2010*,

Falkland, AC 1993, *Hydrology and water management on small tropical islands*,

Faruqui, A, Hledik, R & Sergici, S 2009, 'Piloting the Smart Grid', *The Electricity Journal*, vol. 22, no. 7, pp. 55-69.

Fien, J & Trainer, T 1993, 'A vision of sustainability', *Environmental education: A pathway to sustainability*, pp. 24-42.

Fink, A 2008, *How to conduct surveys: A step by step guide*, Sage Pubns.

Firth, SK & Lomas, KJ 2009, 'INVESTIGATING CO2 EMISSION REDUCTIONS IN EXISTING URBAN HOUSING USING A COMMUNITY DOMESTIC ENERGY MODEL'

Flick, T & Morehouse, J 2011, 'Smart Grid: What Is It?', in *Securing the Smart Grid*, Syngress, Boston, pp. 1-18.

Forget, F, Hourdin, F, Fournier, R, Hourdin, C, Talagrand, O, Collins, M, Lewis, S, Read, P & Huot, J 1999, 'Improved general circulation models of the Martian atmosphere from the surface to above 80 km', *Journal of Geophysical Research*, vol. 104, no. 24, pp. 1555-24,176.

Friedler, F 2010, 'Process integration, modelling and optimisation for energy saving and pollution reduction', *Applied Thermal Engineering*, vol. 30, no. 16, pp. 2270-80.

Friedrichs, J, 'Global Energy Crunch How Different Parts of the World would react to a Peak Oil Scenario'

Fürst, P 1999, 'Nutritional Status of mothers and young children in Maldives–How can it be improved?'

Gadgil, A 1998, 'Drinking water in developing countries', *Annual review of energy and the environment*, vol. 23, no. 1, pp. 253-86.

Gaggioli, R 1983, 'Second law analysis for process and energy engineering', Oxford University Press, pp. 3-50

Gallagher, B 2011, 'Peak oil analyzed with a logistic function and idealized Hubbert curve', *Energy policy*, vol. 39, no. 2, pp. 790-802.

Giatrakos, GP, Tsoutsos, TD & Zografakis, N 2009, 'Sustainable power planning for the island of Crete', *Energy Policy*, vol. 37, no. 4, pp. 1222-38.

Goodstein, D 2005, *Out of gas: the end of the age of oil*, WW Norton & Company.

Gordic, D, Babic, M, Jovicic, N, Sustersic, V, Koncalovic, D & Jelic, D 2010, 'Development of energy management system - Case study of Serbian car manufacturer', *Energy Conversion and Management*, vol. 51, no. 12, pp. 2783-90.

Gössling, S, Peeters, P, Hall, CM, Ceron, J-P, Dubois, G, Lehmann, LV & Scott, D 2011, 'Tourism and water use: Supply, demand, and security. An international review', *Tourism Management*, vol. In Press, Corrected Proof

Gross, R, Leach, M & Bauen, A 2003, 'Progress in renewable energy', *Environment International*, vol. 29, no. 1, pp. 105-22.

Guinée, J 2002, 'Handbook on life cycle assessment operational guide to the ISO standards', *The international journal of life cycle assessment*, vol. 7, no. 5, pp. 311-3.

Gumerman, E, Koomey, JG & Brown, MA 2001, 'Strategies for cost-effective carbon reductions: a sensitivity analysis of alternative scenarios', *Energy policy*, vol. 29, no. 14, pp. 1313-23.

Gyamfi, S 2010, *Demand Response Assessment and Modelling of Peak Electricity Demand in the Residetial Sector: Information and Communication Requirements* University of Canterbury, Christchurch.

Ha, F & Isaksen, L 1979, 'Impacts of dispersed storage and generation on distribution planning and operating practices', Institute of Electrical and Electronics Engineers, p. 29

Hadjsaid, N, Canard, J & Dumas, F 1999, 'Dispersed generation impact on distribution networks', *IEEE Computer Applications in Power*, vol. 12, no. 2, pp. 22-8.

Hakimi, SM & Moghaddas-Tafreshi, SM 2009, 'Optimal sizing of a stand-alone hybrid power system via particle swarm optimization for Kahnouj area in south-east of Iran', *Renewable Energy,* vol. 34, no. 7, pp. 1855-62.

Hamm, A 2007, *Methodology and Modelling Approach for Strategic Sustainability Analysis of Complex Energy-Environment Systems* University of Canterbury, Christchurch.

Hammond, GP 2000, 'Energy, Environment and Sustainable Development: A UK Perspective', *Process Safety and Environmental Protection,* vol. 78, no. 4, pp. 304-23.

Hammons, TJ 2008, 'Integrating renewable energy sources into European grids', *International Journal of Electrical Power & Energy Systems,* vol. 30, no. 8, pp. 462-75.

Hasanuzzaman, M, Saidur, R & Masjuki, HH 2008, 'Investigation of energy consumption and energy savings of refrigerator-freezer during open and closed door condition', *Journal of Applied Sciences,* vol. 8, no. 10, pp. 1822-31.

Hatziargyriou, N, Asano, H, Iravani, R & Marnay, C 2007, 'Microgrids', *Power and Energy Magazine, IEEE,* vol. 5, no. 4, pp. 78-94.

Hay, JE 2006, 'Climate Risk Profile for the Maldives, Ministry of Environment, Energy and Water, Male''

Heidell, J & Ware, H 2010, 'Is There a Case for Broadband Utility Communications Networks? Valuing and Pricing Incremental Communications Capacity on Electric Utility Smart Grid Networks', *The Electricity Journal,* vol. 23, no. 1, pp. 21-33.

Heijungs, R 1994, 'A generic method for the identification of options for cleaner products', *Ecological economics,* vol. 10, no. 1, pp. 69-81.

Heinberg, R 2005, *The party's over: oil, war and the fate of industrial societies*, New Society Pub.

Herremans, IM & Reid, RE 2002, 'Developing awareness of the sustainability concept', *The Journal of Environmental Education,* vol. 34, no. 1, pp. 16-20.

Himri, Y, Boudghene Stambouli, A & Draoui, B 2009, 'Prospects of wind farm development in Algeria', *Desalination,* vol. 239, no. 1-3, pp. 130-8.

Hirsch, R 2005, 'The inevitable peaking of world oil production', *Bulletin of the Atlantic Council of the United States,* vol. 16, no. 3, pp. 1-10.

Hirsch, R, Bezdek, R & Wendling, R 2006, 'Peaking of world oil production and its mitigation', *Driving climate change: cutting carbon from transportation*, p. 9.

Hirsch, R, L., , Bezdek, R & Wendling, R 2005, 'Peaking of world oil production:Impacts, mitigation, & risk management, Technical report, U.S. Department of Energy, National Energy Technology Laboratory.'

Hirsch, RL 2008, 'Mitigation of maximum world oil production: Shortage scenarios', *Energy policy*, vol. 36, no. 2, pp. 881-9.

Hodge, T 1997, 'Toward a conceptual framework for assessing progress toward sustainability', *Social Indicators Research*, vol. 40, no. 1, pp. 5-98.

Hoffert, M, Caldeira, K, Benford, G, Criswell, D, Green, C, Herzog, H, Jain, A, Kheshgi, H, Lackner, K & Lewis, J 2002, 'Advanced technology paths to global climate stability: energy for a greenhouse planet', *Science*, vol. 298, no. 5595, p. 981.

Holmberga, J & Robèrta, K, 'Backcasting from non-overlapping sustainability principles—a framework for strategic planning', *Ecology*, vol. 7, pp. 291-308.

HOMER Energy LLC, 'HOMER. <http://www.homerenergy.com/software.asp>, (accessed 10.05.2010)'

Hong, G-B, Su, T-L, Lee, J-D, Hsu, T-C & Chen, H-W 2010, 'Energy conservation potential in Taiwanese textile industry', *Energy policy*, vol. 38, no. 11, pp. 7048-53.

Houri, A 2006, 'Solar water heating in Lebanon: Current status and future prospects', *Renewable Energy*, vol. 31, no. 5, pp. 663-75.

Hsu, C-W, Chang, P-L & Hsiung, C-M 2011, 'Construction and application of a performance assessment model for energy conservation and carbon reduction industries', *International Journal of Hydrogen Energy*, vol. In Press, Corrected Proof

Hubbert, M 1956, 'Nuclear Energy and the Fossil Fuel', *Drilling and Production Practice*

Hunter, R & Elliot, G 1994, *Wind-diesel systems: a guide to the technology and its implementation*, Cambridge Univ Pr.

Hyman, EL 1983, 'How to conduct a rural energy survey in a developing country', *Journal Name: Renewable Sources Energy; (); Journal Volume: 1:2*, pp. Medium: X; Size: Pages: 137-49.

Ibrahim, H, Younès, R, Basbous, T, Ilinca, A & Dimitrova, M 2011, 'Optimization of diesel engine performances for a hybrid wind-diesel system with compressed air energy storage', *Energy*, vol. 36, no. 5, pp. 3079-91.

Ibrahim, H, Younès, R, Ilinca, A, Dimitrova, M & Perron, J 2010, 'Study and design of a hybrid wind-diesel-compressed air energy storage system for remote areas', *Applied Energy,* vol. 87, no. 5, pp. 1749-62.

IEA 2008, 'World Energy Outlook', *Organisation for Economic Co-operation and Development OECD*

Iqbal, MT 2004, 'A feasibility study of a zero energy home in Newfoundland', *Renewable Energy,* vol. 29, no. 2, pp. 277-89.

Jackson, J 2010, 'Improving energy efficiency and smart grid program analysis with agent-based end-use forecasting models', *Energy Policy,* vol. 38, no. 7, pp. 3771-80.

Jameel, A 2007, 'A model to integrate the management of hazards and disasters in the national sustainable development planning of the Maldives'

Järventausta, P, Repo, S, Rautiainen, A & Partanen, J 2010, 'Smart grid power system control in distributed generation environment', *Annual Reviews in Control,* vol. 34, no. 2, pp. 277-86.

Jenkins, N 1995, 'Embedded generation', *Power Engineering Journal,* vol. 9, no. 3, pp. 145-50.

Jeurissen, R 2000, 'John Elkington, Cannibals With Forks: The Triple Bottom Line of 21st Century Business', *Journal of Business Ethics,* vol. 23, no. 2, pp. 229-31.

Jiang, MP & Tovey, K 2010, 'Overcoming barriers to implementation of carbon reduction strategies in large commercial buildings in China', *Building and Environment,* vol. 45, no. 4, pp. 856-64.

Kabir, G, Abubakar, AI & El-Nafaty, UA 2010, 'Energy audit and conservation opportunities for pyroprocessing unit of a typical dry process cement plant', *Energy,* vol. 35, no. 3, pp. 1237-43.

Kaldellis, JK 2007, 'An integrated model for performance simulation of hybrid wind-diesel systems', *Renewable Energy,* vol. 32, no. 9, pp. 1544-64.

Kaldellis, JK & Kavadias, KA 2007, 'Cost-benefit analysis of remote hybrid wind-diesel power stations: Case study Aegean Sea islands', *Energy policy,* vol. 35, no. 3, pp. 1525-38.

Kanase-Patil, AB, Saini, RP & Sharma, MP 2011, 'Sizing of integrated renewable energy system based on load profiles and reliability index for the state of Uttarakhand in India', *Renewable Energy,* vol. 36, no. 11, pp. 2809-21.

Karakosta, C & Askounis, D 2010, 'Developing countries' energy needs and priorities under a sustainable development perspective: A linguistic decision support approach', *Energy for Sustainable Development,* vol. 14, no. 4, pp. 330-8.

Kempton, W 2010, 'Analysis: Large-Scale Integration of Renewable Energy', in *Renewable Energy Systems*, Academic Press, Boston, pp. 75-125.

Khan, MJ & Iqbal, MT 2005, 'Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland', *Renewable Energy,* vol. 30, no. 6, pp. 835-54.

Kikuchi, E, Bristow, D & Kennedy, CA 2009, 'Evaluation of region-specific residential energy systems for GHG reductions: Case studies in Canadian cities', *Energy Policy,* vol. 37, no. 4, pp. 1257-66.

Kontorovich, AE 2009, 'Estimate of global oil resource and the forecast for global oil production in the 21st century', *Russian Geology and Geophysics,* vol. 50, no. 4, pp. 237-42.

Kowalski, K, Stagl, S, Madlener, R & Omann, I 2009, 'Sustainable energy futures: Methodological challenges in combining scenarios and participatory multi-criteria analysis', *European Journal of Operational Research,* vol. 197, no. 3, pp. 1063-74.

Kranzl, L, Stadler, M, Huber, C, Haas, R, Ragwitz, M, Brakhage, A, Gula, A & Figorski, A 2006, 'Deriving efficient policy portfolios promoting sustainable energy systems--Case studies applying Invert simulation tool', *Renewable Energy,* vol. 31, no. 15, pp. 2393-410.

Krumdieck, S 2004, 'Rise of the sustainable civilization from the ashes of the oil empire:The nature of social change and the role of engineering', *Engineers for Social Responsibility, 18th National Conference*

Krumdieck, S 2007, 'Feedback Control Model of Regional Energy Systems
IPENZ engineering TreNz 2007-002'

Krumdieck, S & Hamm, A 2009, 'Strategic analysis methodology for energy systems with remote island case study', *Energy Policy,* vol. 37, no. 9, pp. 3301-13.

Krumdieck, S, Page, S & Dantas, A 2010, 'Urban form and long-term fuel supply decline: A method to investigate the peak oil risks to essential activities', *Transportation Research Part A: Policy and Practice,* vol. 44, no. 5, pp. 306-22.

Kunstler, J 2005, *The long emergency,* Atlantic Monthly Press.

Lackner, J & Dizio, P 1994, 'Rapid adaptation to Coriolis force perturbations of arm trajectory', *Journal of neurophysiology,* vol. 72, no. 1, p. 299.

Laherrère, J & Valery, P 2003, 'Modelling future oil production, population and the economy', Citeseer

Lambert, T, Gilman, P & Lilienthal, P 2006, 'Micropower system modeling with HOMER', *Integration of alternative sources of energy*, pp. 379–418.

Lange, M 2005, 'On the uncertainty of wind power predictions—Analysis of the forecast accuracy and statistical distribution of errors', *Journal of Solar Energy Engineering,* vol. 127, p. 177.

Larsen, RK, Miller, F & Thomalla, F 2008, 'Vulnerability in the context of post 2004 Indian Ocean Tsunami recovery: Lessons for building more resilient coastal communities', *SEI Risk, Livelihoods & Vulnerability Report, Stockholm Environment Institute, Stockholm, Sweden*

Lasseter, R & Piagi, P 2004, 'Microgrid: A conceptual solution', Citeseer, pp. 4285-91

Lee, H, Chase, S & Dugan, R 1984, 'Overvoltage considerations for interconnecting dispersed generators with wye-grounded distribution feeders', *IEEE Transactions on Power Apparatus and Systems,* pp. 3587-94.

Lee, SC, Sum Ng, DK, Yee Foo, DC & Tan, RR 2009, 'Extended pinch targeting techniques for carbon-constrained energy sector planning', *Applied Energy,* vol. 86, no. 1, pp. 60-7.

Li, J 2008, 'Towards a low-carbon future in China's building sector--A review of energy and climate models forecast', *Energy Policy,* vol. 36, no. 5, pp. 1736-47.

Li, Y, Li, J, Qiu, Q & Xu, Y 2010, 'Energy auditing and energy conservation potential for glass works', *Applied Energy,* vol. 87, no. 8, pp. 2438-46.

Lin, W-M, Gow, H-J & Tsai, M-T 2010a, 'Electricity price forecasting using Enhanced Probability Neural Network', *Energy Conversion and Management,* vol. 51, no. 12, pp. 2707-14.

Lin, W-M, Gow, H-J & Tsai, M-T 2010b, 'An enhanced radial basis function network for short-term electricity price forecasting', *Applied Energy,* vol. 87, no. 10, pp. 3226-34.

Lior, N 2010, 'Sustainable energy development: The present (2009) situation and possible paths to the future', *Energy,* vol. 35, no. 10, pp. 3976-94.

Liu, DY, Chang, WR & Lin, JY 2004, 'Performance comparison with effect of door opening on variable and fixed frequency refrigerators/freezers', *Applied Thermal Engineering,* vol. 24, no. 14, pp. 2281-92.

Liu, P, Pistikopoulos, EN & Li, Z 2010, 'An energy systems engineering approach to the optimal design of energy systems in commercial buildings', *Energy policy,* vol. 38, no. 8, pp. 4224-31.

Liu, X, Hewings, GJD & Wang, S 2009, 'Evaluation on the impacts of the implementation of civil building energy efficiency standards on Chinese economic system and environment', *Energy and Buildings,* vol. 41, no. 10, pp. 1084-90.

Löf, G, Duffie, J & Smith, C 1966, 'World distribution of solar radiation', *Solar Energy,* vol. 10, no. 1, pp. 27-37.

Lomborg, B 2001, 'The truth about the environment', *The Economist,* vol. 4, pp. 63-5.

Lund, H 2006, 'Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply', *Renewable Energy,* vol. 31, no. 4, pp. 503-15.

Lund, H 2010, 'The implementation of renewable energy systems. Lessons learned from the Danish case', *Energy,* vol. 35, no. 10, pp. 4003-9.

Lund, H & Andersen, AN 2005, 'Optimal designs of small CHP plants in a market with fluctuating electricity prices', *Energy Conversion and Management,* vol. 46, no. 6, pp. 893-904.

Lund, H, Duic, N, Krajacic, G & Graça Carvalho, Md 2007, 'Two energy system analysis models: A comparison of methodologies and results', *Energy,* vol. 32, no. 6, pp. 948-54.

Lund, H & Mathiesen, BV 2009, 'Energy system analysis of 100% renewable energy systems--The case of Denmark in years 2030 and 2050', *Energy,* vol. 34, no. 5, pp. 524-31.

Lund, H & Münster, E 2003, 'Modelling of energy systems with a high percentage of CHP and wind power', *Renewable Energy,* vol. 28, no. 14, pp. 2179-93.

Lund, H, Salgi, G, Elmegaard, B & Andersen, AN 2009, 'Optimal operation strategies of compressed air energy storage (CAES) on electricity spot markets with fluctuating prices', *Applied Thermal Engineering,* vol. 29, no. 5-6, pp. 799-806.

Lundsager, P, 'Integration of renewable energy into local and regional power supply', *Renewable Energy,* vol. 8, no. 1-4, pp. 117-22.

Lundsager, P & Bindner, H 1994, 'A simple, robust & reliable wind diesel concept for remote power supply', *Renewable Energy,* vol. 5, no. 1-4, pp. 626-30.

Lynch, MC 2003, 'The new pessimism about petroleum resources: Debunking the hubbert model (and hubbert modelers)', *Minerals & Energy-Raw Materials Report*, vol. 18, no. 1, pp. 21-32.

Maggio, G & Cacciola, G 2009, 'A variant of the Hubbert curve for world oil production forecasts', *Energy policy*, vol. 37, no. 11, pp. 4761-70.

Mallah, S & Bansal, NK 2010, 'Renewable energy for sustainable electrical energy system in India', *Energy Policy*, vol. 38, no. 8, pp. 3933-42.

Mansouri, I, Newborough, M & Probert, D 1996, 'Energy consumption in UK households: Impact of domestic electrical appliances', *Applied Energy*, vol. 54, no. 3, pp. 211-85.

Marcuse, W, Bodin, L, Cherniavsky, E & Sanborn, Y 1996, *Dynamic time dependent model for the analysis of alternative energy policies*, BNL-19406, Brookhaven National Lab., Upton, NY (USA)

Martinot, E, Cabraal, A & Mathur, S 2001, 'World Bank/GEF solar home system projects: experiences and lessons learned 1993-2000', *Renewable and Sustainable Energy Reviews*, vol. 5, no. 1, pp. 39-58.

Mathiesen, BV, Lund, H & Karlsson, K, '100% Renewable energy systems, climate mitigation and economic growth', *Applied Energy*, vol. In Press, Corrected Proof

Meadows, D, Meadows, D, Randers, J & Behrens, W 1972, *The limits to growth: a report for the Club of Rome's project on the predicament of mankind*, Universe Books New York.

Meadows, D, Randers, J & Meadows, D 2004, *The limits to growth: the 30-year update*, Chelsea Green.

Mebratu, D 1998, 'Sustainability and sustainable development: Historical and conceptual review', *Environmental Impact Assessment Review*, vol. 18, no. 6, pp. 493-520.

Meng, M & Niu, D 2011, 'Annual electricity consumption analysis and forecasting of China based on few observations methods', *Energy Conversion and Management*, vol. 52, no. 2, pp. 953-7.

Ministry of Planning and National Development, M, Maldives 2007, 'Statistical yearbook of Maldives'. Ministry of Planning and National Development, Male', Maldives, Male'.

Mitchell, J 1983, *Energy engineering*, John Wiley & Sons.

Mitra, I 2008, *Optimum Utilization of Renewable Energy for Electrification of Small Islands in Developing Countries*, kassel university press GmbH.

Mitra, I, Degner, T & Braun, M 2008, 'Distributed generation and microgrids for small island electrification in developing countries: A review', *SESI Journal, Solar Energy Society of India,* vol. 18, no. 1, pp. 6-20.

Mondal, AH & Denich, M 2010, 'Hybrid systems for decentralized power generation in Bangladesh', *Energy for Sustainable Development,* vol. 14, no. 1, pp. 48-55.

MPND 2007, 'Ministry of Planning and National Development (MPND), Male', Maldives', *Statistical Yearbook of Maldives*

MPND 2009, 'Ministry of Planning and National Development, Male', Maldives', *Statistical year book*

Nagrath, I 2005, *Control systems engineering*, New Age International.

Nair, N-KC & Zhang, L 2009, 'SmartGrid: Future networks for New Zealand power systems incorporating distributed generation', *Energy Policy,* vol. 37, no. 9, pp. 3418-27.

Nakata, T, Silva, D & Rodionov, M 2011, 'Application of energy system models for designing a low-carbon society', *Progress in Energy and Combustion Science,* vol. 37, no. 4, pp. 462-502.

National Resources Canada, *RETScreen International.* *<http://www.retscreen.net/ang/home.php> (accessed 10.05.2010),*

Nayar, C 2008, 'Remote area micro-grid system using diesel driven doubly fed induction generators, photovoltaics and wind generators', pp. 1081-6

Nema, P, Nema, RK & Rangnekar, S 2009, 'A current and future state of art development of hybrid energy system using wind and PV-solar: A review', *Renewable and Sustainable Energy Reviews,* vol. 13, no. 8, pp. 2096-103.

Niemi, R & Lund, PD 2010, 'Decentralized electricity system sizing and placement in distribution networks', *Applied Energy,* vol. 87, no. 6, pp. 1865-9.

Norman, W & MacDonald, C 2004, 'Getting to the Bottom of" Triple Bottom Line"', *Business Ethics Quarterly*, pp. 243-62.

Notton, G, Muselli, M & Louche, A 1996, 'Autonomous hybrid photovoltaic power plant using a back-up generator: a case study in a Mediterranean island', *Renewable Energy,* vol. 7, no. 4, pp. 371-91.

Omer, AM 2008, 'Energy, environment and sustainable development', *Renewable and Sustainable Energy Reviews,* vol. 12, no. 9, pp. 2265-300.

Onar, OC, Uzunoglu, M & Alam, MS 2008, 'Modeling, control and simulation of an autonomous wind turbine/photovoltaic/fuel cell/ultra-capacitor hybrid power system', *Journal of Power Sources*, vol. 185, no. 2, pp. 1273-83.

Orecchini, F & Santiangeli, A 2011, 'Beyond smart grids - The need of intelligent energy networks for a higher global efficiency through energy vectors integration', *International Journal of Hydrogen Energy*, vol. In Press, Corrected Proof

Ortolano, L 1984, 'Environmental planning and decision making'

Østergaard, PA 2005, 'Modelling grid losses and the geographic distribution of electricity generation', *Renewable Energy*, vol. 30, no. 7, pp. 977-87.

Østergaard, PA 2009, 'Reviewing optimisation criteria for energy systems analyses of renewable energy integration', *Energy*, vol. 34, no. 9, pp. 1236-45.

Owen, NA, Inderwildi, OR & King, DA 2010, 'The status of conventional world oil reserves--Hype or cause for concern?', *Energy policy*, vol. 38, no. 8, pp. 4743-9.

Paatero, J & Lund, P 2007, 'Effects of large-scale photovoltaic power integration on electricity distribution networks', *Renewable Energy*, vol. 32, no. 2, pp. 216-34.

Pace, ML & Groffmann, PM (eds.) 1998, *Successes, Limitations and frontiers in Ecosystem Science*, Springer-verlag New York, Inc, New York.

Palm, WJ 2000, 'Modelling, Analysis, and Control of Dynamic Systems, John Wiley & Sons Inc., New York.'

Pedregal, DJ & Trapero, JR 2010, 'Mid-term hourly electricity forecasting based on a multi-rate approach', *Energy Conversion and Management*, vol. 51, no. 1, pp. 105-11.

Pfeiffer, A, Koschenz, M & Wokaun, A 2005, 'Energy and building technology for the 2000 W society--Potential of residential buildings in Switzerland', *Energy and Buildings*, vol. 37, no. 11, pp. 1158-74.

Phuangpornpitak, N & Kumar, S 2011, 'User acceptance of diesel/PV hybrid system in an island community', *Renewable Energy*, vol. 36, no. 1, pp. 125-31.

Pillai, JR, Heussen, K & Østergaard, PA 2011, 'Comparative analysis of hourly and dynamic power balancing models for validating future energy scenarios', *Energy*, vol. In Press, Corrected Proof

Pouresmaeil, E, Gomis-Bellmunt, O, Montesinos-Miracle, D & Bergas-Jané, J 2011, 'Multilevel converters control for renewable energy integration to the power grid', *Energy*, vol. 36, no. 2, pp. 950-63.

Powell, J, Pearce, D & Craighill, A 1997, 'Approaches to valuation in LCA Impact assessment', *The international journal of life cycle assessment,* vol. 2, no. 1, pp. 11-5.

Rasmusson, E & Carpenter, T 1982, 'Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño', *Monthly Weather Review,* vol. 110, no. 5, pp. 354-84.

Read, R & University. United Nations, WI 2001, *Growth, economic development and structural transition in small vulnerable states,* World Institute for Development Economics Research, United Nations University, Helsinki.

Rechsteiner, R 2004, 'Ten Steps to a Sustainable Energy Future'

Rehman, S, El-Amin, IM, Ahmad, F, Shaahid, SM, Al-Shehri, AM, Bakhashwain, JM & Shash, A 2007, 'Feasibility study of hybrid retrofits to an isolated off-grid diesel power plant', *Renewable and Sustainable Energy Reviews,* vol. 11, no. 4, pp. 635-53.

Rehman, S, Halawani, T & Husain, T 1994, 'Weibull parameters for wind speed distribution in Saudi Arabia', *Solar Energy,* vol. 53, no. 6, pp. 473-9.

Reiche, K, Covarrubias, A & Martinot, E 2000, 'Expanding electricity access to remote areas: off-grid rural electrification in developing countries', *Fuel,* vol. 1, no. 1.2, p. 1.4.

Richardson, I, Thomson, M, Infield, D & Delahunty, A 2009, 'Domestic lighting: A high-resolution energy demand model', *Energy and Buildings,* vol. 41, no. 7, pp. 781-9.

Rizy, D, Jewell, W & Stovall, J 1985, 'Operational and design considerations for electric distribution systems with dispersed storage and generation (DSG)', *IEEE Transactions on Power Apparatus and Systems*, pp. 2864-71.

Robert, K 2002, *The Natural Step story: Seeding a quiet revolution*, New Society Pub.

Rohatgi, J & Nelson, V 1994, 'Wind Characteristics, an analysis for the generation of wind power', *Texas, USA*

Rosemann, A & Suvagau, C 2008, 'Methodology to calculate the energy consumption for lighting in buildings', IEEE, pp. 1-4

Roy, A, Kedare, SB & Bandyopadhyay, S 2010, 'Optimum sizing of wind-battery systems incorporating resource uncertainty', *Applied Energy,* vol. 87, no. 8, pp. 2712-27.

Rozakis, S, Soldatos, PG, Papadakis, G, Kyritsis, S & Papantonis, D 1997, 'Evaluation of an integrated renewable energy system for electricity generation in rural areas', *Energy policy*, vol. 25, no. 3, pp. 337-47.

Sadler, B & Jacobs, P 1990, 'A key to tomorrow: on the relationship of environmental assessment and sustainable development', *Learning to Live Drug Free: A Curriculum Model for Prevention*, p. 2.

Sampat, P 2000, 'Groundwater shock', *World Watch*, vol. 12, no. 1, pp. 10-22.

Seebregts, A, Goldstein, G & Smekens, K, 'Energy/environmental modeling with the MARKAL family of models'

Segar, DA 1998, 'Introduction to Ocean Sciences, Wadsworth Publishing'

Seinfeld, J & Pandis, S 1998, 'From air pollution to climate change', *Atmospheric Chemistry and Physics, John Wiley & Sons, New York*, vol. 1326

Sendegeya, A, Lugujjo, E, Da Silva, IP & Amelin, M 2006, 'Feasibility of conserving energy through education: The case of Uganda as a developing country', in JA Mwakali & G Taban-Wani (eds), *Proceedings from the International Conference on Advances in Engineering and Technology*, Elsevier Science Ltd, Oxford, pp. 385-94.

Shafie-khah, M, Moghaddam, MP & Sheikh-El-Eslami, MK 2011, 'Price forecasting of day-ahead electricity markets using a hybrid forecast method', *Energy Conversion and Management*, vol. 52, no. 5, pp. 2165-9.

Shailaja, R 2000, 'Women, energy and sustainable development', *Energy for Sustainable Development*, vol. 4, no. 1, pp. 45-64.

Shareef, A 2009, 'Numerical Analysis of Convective Storm Development over Maldives'

Shenoy, UV 2010, 'Targeting and design of energy allocation networks for carbon emission reduction', *Chemical Engineering Science*, vol. 65, no. 23, pp. 6155-68.

Simmons, M 2005, *Twilight in the desert: the coming Saudi oil shock and the world economy*, Wiley.

Singhal, D & Swarup, KS 2011, 'Electricity price forecasting using artificial neural networks', *International Journal of Electrical Power & Energy Systems*, vol. 33, no. 3, pp. 550-5.

Skrebowski, C 2004, 'Oil Fields Mega Projects–2004 Petroleum Review'. January.

Sluka, R & Miller, M 1998, 'Coral mining in the Maldives', *Coral Reefs*, vol. 17, no. 3, pp. 288-.

Soratana, K & Marriott, J 2010, 'Increasing innovation in home energy efficiency: Monte Carlo simulation of potential improvements', *Energy and Buildings*, vol. 42, no. 6, pp. 828-33.

Sørensen, B 2004, *Renewable energy: its physics, engineering, use, environmental impacts, economy, and planning aspects*, Academic Press.

Stadler, I 2008, 'Power grid balancing of energy systems with high renewable energy penetration by demand response', *Utilities Policy*, vol. 16, no. 2, pp. 90-8.

Stadler, M, Kranzl, L, Huber, C, Haas, R & Tsioliaridou, E 2007, 'Policy strategies and paths to promote sustainable energy systems--The dynamic Invert simulation tool', *Energy Policy*, vol. 35, no. 1, pp. 597-608.

Stockholm Environment Institute, *LEAP applications.* *<http://www.energycommunity.org/default.asp?action=45>, (accessed 11.05.2010),*

Strachan, N & Kannan, R 2008, 'Hybrid modelling of long-term carbon reduction scenarios for the UK', *Energy Economics*, vol. 30, no. 6, pp. 2947-63.

Strauss, P, Kleinkauf, W, Reekers, J, Cramer, G & Betzios, G, 'Kythnos Island–19 Years Experience of Renewable Energy Integration', *Proceedings of Renewable Energies for Islands-towards*, vol. 100, pp. 14-6.

Streimikiene, D, Ciegis, R & Grundey, D 2007, 'Energy indicators for sustainable development in Baltic States', *Renewable and Sustainable Energy Reviews*, vol. 11, no. 5, pp. 877-93.

Subhash, C & Satsangi, PS 1990, 'An integrated planning and implementation-strategy for rural energy systems', *Energy*, vol. 15, no. 10, pp. 913-20.

Sumer, KK, Goktas, O & Hepsag, A 2009, 'The application of seasonal latent variable in forecasting electricity demand as an alternative method', *Energy Policy*, vol. 37, no. 4, pp. 1317-22.

Tao, S, Weisheng, W, Huizhu, D & Yi-han, Y 2003, 'Voltage Fluctuation and Flicker Caused by Wind Power Generation', *POWER SYSTEM TECHNOLOGY-BEIJING-*, vol. 27, no. 12, pp. 62-6.

Tatiétsé, TT, Villeneuve, P, Ngundam, J & Kenfack, F 2002, 'Contribution to the analysis of urban residential electrical energy demand in developing countries', *Energy*, vol. 27, no. 6, pp. 591-606.

Taylor, JW 2010, 'Triple seasonal methods for short-term electricity demand forecasting', *European Journal of Operational Research*, vol. 204, no. 1, pp. 139-52.

Thumann, A & Mehta, D 2001, *Handbook of energy engineering*, The Fairmont Press, Inc.

Turner, GM 2008, 'A comparison of The Limits to Growth with 30 years of reality', *Global Environmental Change*, vol. 18, no. 3, pp. 397-411.

Turner, W & Doty, S 2006, *Energy management handbook*, Fairmont Pr.

Ulleberg, Ø, Nakken, T & Eté, A 2010, 'The wind/hydrogen demonstration system at Utsira in Norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools', *International Journal of Hydrogen Energy*, vol. 35, no. 5, pp. 1841-52.

van Alphen, K & Hekkert, MP 2008, 'Renewable energy technologies in the Maldives - Realizing the potential', *Renewable & Sustainable Energy Reviews*, vol. 12, pp. 162-80.

van Alphen, K, van Sark, WGJHM & Hekkert, MP 2007, 'Renewable energy technologies in the Maldives--determining the potential', *Renewable and Sustainable Energy Reviews*, vol. 11, no. 8, pp. 1650-74.

Van Heddeghem, W, Vereecken, W, Colle, D, Pickavet, M & Demeester, P 2011, 'Distributed computing for carbon footprint reduction by exploiting low-footprint energy availability', *Future Generation Computer Systems*, vol. In Press, Accepted Manuscript

Vecchi, G & Harrison, D 2010, 'Tropical Pacific Sea Surface Temperature Anomalies, El Niño, and Equatorial Westerly Wind Events*'

Vienna University of Technology, 'Invert.<http://www.invert.at/>, accessed 19.05.2010'

Vose, D 2008, *Risk analysis: a quantitative guide*, John Wiley & Sons Inc.

Voudouris, V, Stasinopoulos, D, Rigby, R & Di Maio, C 2011, 'The ACEGES laboratory for energy policy: Exploring the production of crude oil', *Energy policy*, vol. In Press, Corrected Proof

Wackernagel, M & Rees, W 1996, *Our ecological footprint: reducing human impact on the earth*, New Society Pub.

Wasynczuk, O 1984, 'Integration of dispersed PV generation into utility distribution systems: stability, interaction and fault tolerance', pp. 2145-51

Weston, K 1992, *Energy conversion*, West Pub. Co.

Wichert, B 1997, 'PV-diesel hybrid energy systems for remote area power generation--a review of current practice and future developments', *Renewable and Sustainable Energy Reviews*, vol. 1, no. 3, pp. 209-28.

Williams, RH 2001, 'Addressing challenges to sustainable development with innovative energy technologies in a competitive electric industry', *Energy for Sustainable Development,* vol. 5, no. 2, pp. 48-73.

Wissner, M 2011a, 'ICT, growth and productivity in the German energy sector - On the way to a smart grid?', *Utilities Policy,* vol. 19, no. 1, pp. 14-9.

Wissner, M 2011b, 'The Smart Grid - A saucerful of secrets?', *Applied Energy,* vol. 88, no. 7, pp. 2509-18.

Wright, A & Firth, S 2007, 'The nature of domestic electricity-loads and effects of time averaging on statistics and on-site generation calculations', *Applied Energy,* vol. 84, no. 4, pp. 389-403.

Yamaguchi, Y, Shimoda, Y & Mizuno, M 2007, 'Transition to a sustainable urban energy system from a long-term perspective: Case study in a Japanese business district', *Energy and Buildings,* vol. 39, no. 1, pp. 1-12.

Yan, X & Crookes, RJ 2009, 'Reduction potentials of energy demand and GHG emissions in China's road transport sector', *Energy Policy,* vol. 37, no. 2, pp. 658-68.

Yao, R & Steemers, K 2005, 'A method of formulating energy load profile for domestic buildings in the UK', *Energy and Buildings,* vol. 37, no. 6, pp. 663-71.

Zaharim, A, Razali, A, Abidin, R & Sopian, K 2009, 'Fitting of Statistical Distributions to Wind Speed Data in Malaysia', *European Journal of Scientific Research,* vol. 26, no. 1, pp. 6-12.

Zhiqun, W, Shouzhen, Z, Shuangxi, Z, Renle, H & Liangui, W 2004, 'Impacts of distributed generation on distribution system voltage profile [J]', *Automation of Electric Power Systems,* vol. 16

Zhou, W, Lou, C, Li, Z, Lu, L & Yang, H 2010, 'Current status of research on optimum sizing of stand-alone hybrid solar-wind power generation systems', *Applied Energy,* vol. 87, no. 2, pp. 380-9.

Zhu, Y 2006, 'Applying computer-based simulation to energy auditing: A case study', *Energy and Buildings,* vol. 38, no. 5, pp. 421-8.

Zubair, S, Bowen, D & Elwin, J 2011, 'Not quite paradise: Inadequacies of environmental impact assessment in the Maldives', *Tourism Management,* vol. 32, no. 2, pp. 225-34.

Appendix A: Generated Load Curves

Table A1- presents household's hourly electric power demand (primary load) and deferrable load for every household in the sample with moderate constraints.

Table A2- presents household's hourly electric power demand (primary load) and deferrable load for every household in the sample with severe constraints.

Table A3- presents hourly electric power demand (primary load) and deferrable load of Government institutions and commercial/industrial sector with moderate constraints.

Table A4- presents hourly electric power demand (primary load) and deferrable load of Government institutions and commercial/industrial sector with severe constraints.

Table A5- presents the final calculated load curves for the island community: present unconstrained demand, moderately constrained and severely constrained demand.

A1- Hourly electric power demand (primary load) and deferrable load of households with moderate constraints

HH code	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13
1000	300	300	300	300	300	300	300	330	230	130	130	130	130
1002	305	305	305	305	305	305	305	1120	210	210	210	30	30
1004	570	570	570	570	570	570	570	530	240	249	750	1750	230
1005	205	205	205	205	205	205	40	30	30	30	30	30	30
1006	300	300	300	300	300	300	300	115	30	30	30	30	30
1008	180	180	180	180	180	180	180	105	0	0	0	0	0
1009	690	690	690	690	690	690	690	690	230	115	115	60	60
1016	480	480	480	480	480	480	480	255	115	115	115	115	115
1019	300	300	300	300	300	300	300	135	30	120	120	30	30
1020	210	210	210	210	210	210	210	210	30	30	30	30	30
1021	390	390	390	390	390	390	390	200	115	115	115	30	30
1023	210	210	210	210	210	210	210	30	30	30	30	30	30
1024	120	120	120	120	120	120	120	30	30	30	30	30	30
1025	205	205	205	205	205	205	205	205	30	30	30	30	30
1029	390	390	390	390	390	390	390	390	115	115	30	30	30
1031	300	300	300	300	300	300	300	115	115	85	175	175	30
1032	480	480	480	480	480	480	480	200	115	30	30	30	30
1038	300	300	300	300	300	300	300	115	205	205	205	30	30
1044	320	320	320	320	320	320	320	115	115	30	30	30	30
1048	215	215	215	215	215	215	215	200	115	180	180	30	30
1053	320	320	320	320	320	320	320	200	200	135	135	30	30
1054	340	340	340	340	340	340	340	200	115	200	200	30	30
1062	300	300	300	300	300	300	300	115	115	205	205	30	30

1068	300	300	300	300	300	300	300	200	200	115	115	115	30
1069	200	200	200	200	200	200	200	115	115	30	110	110	30
1071	305	305	305	305	305	305	305	135	135	110	110	30	30
1075	210	210	210	210	210	210	210	115	110	205	205	30	30
1087	270	270	270	270	270	270	270	85	85	0	0	0	0
1089	300	300	300	300	300	300	300	130	30	200	200	30	30
1094	425	425	425	425	425	425	425	330	280	210	210	30	30
1098	335	335	335	335	335	335	335	200	200	110	110	110	30
1099	355	355	355	355	355	355	355	270	270	270	270	110	110
1101	210	210	210	210	210	210	210	85	85	0	0	0	0

HH Code	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-00**	**Deferrable load,kWh**
1000	130	230	130	130	230	170	170	300	300	300	300	1.3
1002	130	480	30	30	230	90	185	290	305	305	305	1.1
1004	230	430	255	255	270	230	430	550	630	630	570	2.3
1005	30	30	230	30	30	60	60	150	150	205	205	0.6
1006	30	115	115	30	30	30	145	235	300	300	300	0.7
1008	0	0	0	0	0	20	105	105	105	180	180	0.4
1009	60	60	135	135	60	60	375	465	465	690	690	2.8
1016	115	115	115	115	115	175	330	390	390	390	480	1.6
1019	115	115	30	30	30	90	235	235	235	235	300	1.1
1020	30	115	115	30	30	70	245	245	245	70	155	0.4
1021	30	115	115	30	30	175	175	235	235	235	390	1.1
1023	30	30	30	30	30	90	90	90	90	90	210	0.6
1024	30	115	115	30	30	70	160	160	160	50	120	0.2

1025	30	30	30	30	30	70	70	245	245	245	245	0.6
1029	30	30	30	30	30	90	175	265	265	265	390	1.2
1031	115	115	30	30	50	90	155	245	245	300	300	0.9
1032	30	115	115	30	30	90	180	180	180	265	480	0.9
1038	30	30	30	30	30	90	90	180	180	300	300	2.1
1044	30	30	30	30	30	110	180	265	265	320	320	0.7
1048	30	30	30	235	235	70	135	225	225	215	215	1
1053	30	30	30	30	30	70	135	135	205	205	320	0.6
1054	30	30	30	110	110	70	175	175	175	340	340	0.7
1062	30	115	115	30	30	70	175	175	175	175	300	0.6
1068	30	30	30	30	30	50	90	180	180	265	300	0.6
1069	30	235	235	30	30	90	195	235	235	200	200	0.7
1071	30	110	110	30	30	90	195	280	280	305	305	0.7
1075	30	30	30	30	30	175	175	275	275	210	210	0.6
1087	0	0	0	0	0	60	60	145	145	145	270	0.2
1089	30	30	30	135	135	90	210	210	210	300	300	0.8
1094	115	115	30	210	210	175	175	225	225	425	425	1.2
1098	30	30	30	30	30	70	70	270	270	335	335	1.6
1099	90	90	30	30	30	175	250	250	250	345	345	1.1
1101	0	0	0	0	0	40	40	230	230	230	210	0.4

A2- Hourly electric power demand (primary load) and deferrable load of households with severe constraints

HH code	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13
1000	300	300	300	300	300	300	300	300	130	85	85	85	85
1002	300	300	300	300	300	300	300	300	170	30	30	30	30
1004	390	390	390	390	390	390	390	390	115	30	30	30	30
1005	205	205	205	205	205	205	40	30	30	30	30	30	30
1006	300	300	300	300	300	300	300	30	30	30	30	30	30
1008	180	180	180	180	180	180	180	85	0	0	0	0	0
1009	660	660	660	660	660	660	660	660	200	115	115	30	30
1016	480	480	480	480	480	480	480	170	30	30	30	30	30
1019	300	300	300	300	300	300	300	50	30	30	30	30	30
1020	210	210	210	210	210	210	210	210	30	30	30	30	30
1021	300	300	300	300	300	300	300	200	30	30	30	30	30
1023	210	210	210	210	210	210	210	30	30	30	30	30	30
1024	120	120	120	120	120	120	120	30	30	30	30	30	30
1025	115	115	115	115	115	115	115	115	30	30	30	30	30
1029	360	360	360	360	360	360	360	360	115	0	0	0	0
1031	270	270	270	270	270	270	270	85	85	0	0	0	0
1032	480	480	480	480	480	480	480	200	115	30	30	30	30
1038	300	300	300	300	300	300	300	115	30	30	30	30	30
1044	300	300	300	300	300	300	300	30	30	30	30	30	30
1048	215	215	215	215	215	215	215	115	30	30	30	30	30
1053	300	300	300	300	300	300	300	115	115	30	30	30	30
1054	255	255	255	255	255	255	255	200	30	30	30	30	30
1062	300	300	300	300	300	300	300	30	30	50	50	30	30

1068	270	270	270	270	270	270	270	115	115	30	30	30	30
1069	200	200	200	200	200	200	200	30	30	30	110	110	30
1071	200	200	200	200	200	200	200	135	135	30	50	30	30
1075	210	210	210	210	210	210	210	30	110	30	30	30	30
1087	270	270	270	270	270	270	270	85	85	0	0	0	0
1089	300	300	300	300	300	300	300	115	30	30	30	30	30
1094	425	425	425	425	425	425	425	330	280	115	115	30	30
1098	270	270	270	270	270	270	270	115	115	30	30	30	30
1099	345	345	345	345	345	345	345	270	270	270	270	110	110
1101	180	180	180	180	180	180	180	0	0	0	0	0	0

HH Code	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-00**	**Deferrable load,kWh**
1000	85	85	85	85	85	85	170	300	300	300	300	0.45
1002	30	30	30	30	30	90	90	265	265	300	300	0.2
1004	30	30	30	30	30	30	195	290	290	390	390	1.3
1005	30	30	230	30	30	60	60	150	150	205	205	0.2
1006	30	30	30	30	30	30	115	115	300	300	300	0.2
1008	0	0	0	0	0	20	105	105	105	180	180	0.2
1009	30	30	30	30	30	30	270	270	270	660	660	1.4
1016	30	30	30	30	30	175	245	245	245	245	480	0.7
1019	30	30	30	30	30	90	235	235	235	235	300	0.6
1020	30	30	30	30	30	70	90	90	90	90	155	0.2
1021	30	30	30	30	30	90	90	90	90	90	300	0.4
1023	30	30	30	30	30	90	90	90	90	90	210	0.2
1024	30	30	30	30	30	50	160	160	160	50	120	0.2

1025	30	30	30	30	30	70	70	155	155	155	155	0.2
1029	0	0	0	0	0	60	145	145	145	145	360	0.3
1031	0	0	0	0	0	40	60	60	60	270	270	0.3
1032	30	115	115	30	30	90	90	90	90	175	480	0.4
1038	30	30	30	30	30	90	90	90	90	300	300	0.5
1044	30	30	30	30	30	70	110	110	110	300	300	0.4
1048	30	30	30	30	30	50	115	115	115	215	215	0.8
1053	30	30	30	30	30	50	70	70	70	70	300	0.3
1054	30	30	30	30	30	50	90	90	90	255	255	0.4
1062	30	30	30	30	30	70	175	175	90	90	300	0.2
1068	30	30	30	30	30	50	90	90	90	90	270	0.6
1069	30	30	30	30	30	70	70	70	70	200	200	0.3
1071	30	110	110	30	30	90	195	195	195	200	200	0.4
1075	30	30	30	30	30	60	110	110	110	210	210	0.2
1087	0	0	0	0	0	60	60	145	145	145	270	0.2
1089	30	30	30	30	30	70	60	60	90	300	300	0.4
1094	30	30	30	30	30	90	90	90	90	425	425	0.6
1098	30	30	30	30	30	50	50	270	270	270	270	0.6
1099	90	90	30	30	30	175	250	250	250	345	345	0.4
1101	0	0	0	0	0	40	40	40	40	40	180	0.2

A3- Hourly electric power demand (primary load) and deferrable load of Government institutions and commercial/industrial sector with moderate constraints

	0-1	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**
Gov. Institutions	191	191	191	191	191	1175	570	4320	5925	5925	5925	5925	6960
Commercial/Industry	420	420	420	420	420	420	420	905	1325	1535	1535	1650	475
	13-14	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-00**	**Deferrable load,kWh**	
Gov. Institutions	5925	4085	1095	60	60	1695	1695	561	456	191	191	1.75	
Commercial/Industry	1535	1450	400	1535	1535	400	1570	1695	1695	1695	400	0.4	

A4- Hourly electric power demand (primary load) and deferrable load of Government institutions and commercial/industrial sector with severe constraints

	0-1	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**
Gov. Institutions	164	164	164	164	164	928	288	4320	5675	5675	5675	5675	6285
Commercial/Industry	300	300	300	300	300	300	300	530	845	1045	1045	1160	435
	13-14	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-00**	**Deferrable load,kWh**	
Gov. Institutions	5675	4085	670	60	60	1028	1028	534	429	164	131	1.5	
Commercial/Industry	1045	1045	300	1085	1085	300	1215	1255	1255	1255	300	0.4	

A5- Final calculated load curves for the island community: present unconstrained demand moderately constrained and severely constrained demand.

	0-1	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**
Present load	39.12	39.12	37.87	38	39	34.75	39.5	42.25	46.87	44.75	27.75	24.87	27.5
Moderate constrained	25.0	25.05	25.05	25.05	25.05	26.03	25.04	22.47	16.87	16.13	17.51	15.38	10.73
Severe constrained	22.9	22.9	22.96	22.96	22.96	23.72	22.6	16.84	12.74	9.851	10.08	9.32	9.02
	13-14	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**	**20-21**	**21-22**	**22-23**	**23-00**	**Deferrable load,kWh**	
Present load	27.87	28.12	27.5	26.37	27.5	41.12	42.25	47.12	45.25	44.62	40.87		
Moderate constrain	11.54	13.03	7.19	6.28	6.90	9.57	16.58	20.78	21.22	23.32	24.97	76.3	
Severely constrained	8.97	7.77	3.94	3.26	3.26	6.77	11.56	13.19	13.39	18.75	22.89	34.8	

Appendix B: Individual Supply System Risks

B1- Risk results of systems simulated for present (unconstrained) load

B2- Risk results of systems simulated for moderately constrained load

B3- Risk results of systems simulated for severely constrained load

B4- Risk results of the final system selected

B1- Systems for present load

B1-1 Risk results for the diesel only systems to supply the present load

Feasibility Risks				
Description		I	P	R
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	1	3
	Cost issues			
Continuous financing problems		4	1	4
Difficulties in finding initial investment due to high initial cost		5	1	5
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		4	5	20
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		2	5	10
Damage of plant due to natural disasters		2	1	2
Environmental Problem Risks				
Accumulation of old machinery, excluding batteries		2	1	2
Large scale contamination of soil/groundwater by waste engine oil		3	1	3
Soil/groundwater contamination due to petroleum fuel spills on land		4	2	8
Sea contamination due to petroleum fuel spills during delivery		4	2	8
Local air pollution due to engine exhausts		2	3	6
Noise pollution due to plant operation		1	4	4

B1-2 Risk results for the diesel-battery systems to supply the present load

Feasibility Risks				
Description		I	P	R
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	2	6
	Cost issues			
Continuous financing problems		4	2	8
Difficulties in finding initial investment due to high initial cost		5	1	5
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		4	5	20
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		2	5	10
Damage of plant due to natural disasters		2	1	2

Environmental Problem Risks			
Accumulation of old machinery, excl. batteries	2	1	2
Large scale contamination of soil/groundwater by waste engine oil	3	1	3
Soil/groundwater contamination due to petroleum fuel spills on land	4	2	8
Sea contamination due to petroleum fuel spills during delivery	5	2	10
Soil/groundwater contamination due to battery spillages	3	3	9
Soil/groundwater contamination due to battery dumping	5	3	15
Local air pollution due to engine exhausts	2	3	6
Noise pollution due to plant operation	1	4	4

B1-3 Risk results for the PV-battery systems to supply the present load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		3	4	12
	Technical issues			
Problem of space limitations for PV panel installations				∞
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	3	9
	Cost issues			
Continuous financing problems		4	5	20
Difficulties in finding initial investment due to high initial cost				∞
Resource Security Risks				
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		2	5	10
Damage of plant due to natural disasters		2	1	2
Solar resource problems due to a prolong period(say two weeks) of no sun		4	2	8
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6
Soil/groundwater contamination due to battery spillages		3	4	12
Soil/groundwater contamination due to battery dumping		3	4	12
Habitat destruction due to land requirements		2	1	2

To supply the present load with PV and battery is not feasible due to high initial cost and the area required for PV installation is a constraint in this case.

B1-4 Risk results for the PV-diesel-battery systems to supply the present load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		3	3	9
	Technical issues			
Problem of space limitations for PV panel installations		1	3	3
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	2	6
	Cost issues			
Continuous financing problems		4	2	8
Difficulties in finding initial investment due to high initial cost		5	2	10
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		3	5	15
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		4	1	4
Solar resource problems due to a prolong period(say two weeks) of no sun		2	2	4
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		2	3	6
Soil/groundwater contamination due to battery spillages		3	2	6
Soil/groundwater contamination due to battery dumping		3	2	6
Habitat destruction due to land requirements		2	1	2
Large scale contamination of soil/groundwater by waste engine oil		3	3	9
Soil/groundwater contamination due to petroleum fuel spills on land		3	3	9
Sea contamination due to petroleum fuel spills during delivery		5	3	15
Local air pollution due to engine exhausts		2	3	6
Noise pollution due to plant operation		2	3	6

B1-5 Risk results for the PV-wind-battery systems to supply the present load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		3	3	9
Premature turbine failure due to corrosion in marine environment		3	3	9
	Technical issues			
Problem of space limitations for wind turbines				∞
Problem of space limitations for PV panel installations				∞
	Application issues			
Repair delays due to long turnaround times		3	3	9
Damage to plant due to improper use		3	4	12
	Cost issues			
Continuous financing problems		4	2	8
Difficulties in finding initial investment due to high initial cost				∞
Resource Security Risks				
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		4	1	4
Solar resource problems due to a prolong period(say two weeks) of no sun		2	2	4
Wind resource problems due to prolong period(two months) of missing power winds		2	2	4
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6
Soil/groundwater contamination due to battery spillages		3	2	6
Soil/groundwater contamination due to battery dumping		3	2	6
Habitat destruction due to land requirements		4	5	20
Noise pollution due to plant operation		2	1	2

B1-6 Risk results for the wind-battery systems to supply the present load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature turbine failure due to corrosion in marine environment		3	5	15
	Technical issues			
Problem of space limitations for wind turbines				∞
	Application issues			
Repair delays due to long turnaround times		3	3	9
Damage to plant due to improper use		3	3	9
	Cost issues			
Continuous financing problems		4	5	20
Difficulties in finding initial investment due to high initial cost				∞
Resource Security Risks				
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		4	1	4
Wind resource problems due to two prolong period of missing power winds		5	2	10
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	3	9
Soil/groundwater contamination due to battery spillages		3	2	6
Soil/groundwater contamination due to battery dumping		3	2	6
Habitat destruction due to land requirements		5	5	25
Noise pollution due to plant operation		2	2	4

B1-7 Risk results for the wind-diesel-battery systems to supply the present load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature turbine failure due to corrosion in marine environment		3	3	9
	Technical issues			
Problem of space limitations for wind turbines		1	5	5
	Application issues			
Repair delays due to long turnaround times		3	3	9
Damage to plant due to improper use		3	3	9
	Cost issues			
Continuous financing problems		3	1	3
Difficulties in finding initial investment due to high initial cost		3	1	3
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		3	5	15

Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil	4	5	20
Damage of plant due to natural disasters	4	1	4
Wind resource problems due to prolong periods(two months) of missing power winds	2	2	4
Environmental Problem Risks			
Accumulation of old machinery, excl. batteries	2	2	4
Soil/groundwater contamination due to battery spillages	3	2	6
Soil/groundwater contamination due to battery dumping	3	2	6
Habitat destruction due to land requirements	3	2	6
Large scale contamination of soil/groundwater by waste engine oil	3	2	6
Soil/groundwater contamination due to petroleum fuel spills on land	3	2	6
Sea contamination due to petroleum fuel spills during delivery	5	2	10
Local air pollution due to engine exhausts	2	2	4
Noise pollution due to plant operation	2	2	4

B1-8 Risk results for the wind-PV-diesel systems to supply the present load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		-	-	-
Premature turbine failure due to corrosion in marine environment		3	3	9
	Technical issues			
Problem of space limitations for wind turbines				∞
Problem of space limitations for PV panel installations		-	-	-
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	3	9
	Cost issues			
Continuous financing problems		4	2	8
Difficulties in finding initial investment due to high initial cost		5	3	15
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		2	5	10
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		4	1	4
Solar resource problems due to a prolong period(say two weeks) of no sun		-	-	
Wind resource problems due to prolong periods(two months)		2	2	4

of missing power winds			
Environmental Problem Risks			
Accumulation of old machinery, excl. batteries	3	2	6
Habitat destruction due to land requirements	3	3	9
Large scale contamination of soil/groundwater by waste engine oil	3	2	6
Soil/groundwater contamination due to petroleum fuel spills on land	3	2	6
Sea contamination due to petroleum fuel spills during delivery	5	2	10
Local air pollution due to engine exhausts	2	2	4
Noise pollution due to plant operation	1	2	2

This system configuration is not feasible due to high number of wind turbines associated.

B1-9 Risk results for the wind-PV-diesel-battery systems to supply the present load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		3	1	3
Premature turbine failure due to corrosion in marine environment		3	3	9
	Technical issues			
Problem of space limitations for wind turbines		1	5	5
Problem of space limitations for PV panel installations		1	1	1
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	4	12
	Cost issues			
Continuous financing problems		4	1	4
Difficulties in finding initial investment due to high initial cost		5	3	15
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		2	5	10
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		4	1	4
Solar resource problems due to a prolong period(say two weeks) of no sun		2	2	4
Wind resource problems due to prolong periods(two months) period of missing power winds		2	2	4
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6

Soil/groundwater contamination due to battery spillages	3	2	6
Soil/groundwater contamination due to battery dumping	3	2	6
Habitat destruction due to land requirements	2	1	2
Large scale contamination of soil/groundwater by waste engine oil	3	2	6
Soil/groundwater contamination due to petroleum fuel spills on land	3	2	6
Sea contamination due to petroleum fuel spills during delivery	5	2	10
Local air pollution due to engine exhausts	2	3	6
Noise pollution due to plant operation	1	2	2

B2- Risk results of systems simulated for moderately constrained load

B2-1 Risk results for the diesel only systems to supply the moderately constrained load

Feasibility Risks				
Description		I	P	R
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	1	3
	Cost issues			
Continuous financing problems		4	2	8
Difficulties in finding initial investment due to high initial cost		5	1	5
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		4	5	20
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		2	1	2
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		2	1	2
Large scale contamination of soil/groundwater by waste engine oil		3	1	3
Soil/groundwater contamination due to petroleum fuel spills on land		3	2	6
Sea contamination due to petroleum fuel spills during delivery		5	1	5
Local air pollution due to engine exhausts		2	2	4
Noise pollution due to plant operation		1	3	3

B2-2 Risk results for the diesel-battery systems to supply the moderately constrained load

Feasibility Risks				
Description		I	P	R

	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	2	6
	Cost issues			
Continuous financing problems		4	3	12
Difficulties in finding initial investment due to high initial cost		5	2	10
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		4	5	20
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		2	1	2
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		2	1	2
Large scale contamination of soil/groundwater by waste engine oil		3	1	3
Soil/groundwater contamination due to petroleum fuel spills on land		3	2	6
Sea contamination due to petroleum fuel spills during delivery		5	2	10
Soil/groundwater contamination due to battery spillages		3	2	6
Soil/groundwater contamination due to battery dumping		3	3	9
Local air pollution due to engine exhausts		2	2	4
Noise pollution due to plant operation		1	2	2

B2-3 Risk results for the PV-battery systems to supply the moderately constrained load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		3	5	15
	Technical issues			
Problem of space limitations for PV panel installations				∞
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	3	9
	Cost issues			
Continuous financing problems		4	4	16
Difficulties in finding initial investment due to high initial cost				∞
Resource Security Risks				
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		4	1	4
Solar resource problems due to a prolong period(say two		5	2	10

weeks) of no sun			
Environmental Problem Risks			
Accumulation of old machinery, excl. batteries	3	2	6
Soil/groundwater contamination due to battery spillages	3	3	9
Soil/groundwater contamination due to battery dumping	3	3	9
Habitat destruction due to land requirements	3	2	6

B2-4 Risk results for the PV-diesel-battery systems to supply the moderately constrained load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		3	3	9
	Technical issues			
Problem of space limitations for PV panel installations		1	3	3
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	3	9
	Cost issues			
Continuous financing problems		4	2	8
Difficulties in finding initial investment due to high initial cost		5	3	15
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		3	5	15
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		3	1	3
Solar resource problems due to a prolong period(say two weeks) of no sun		2	2	4
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6
Soil/groundwater contamination due to battery spillages		3	1	3
Soil/groundwater contamination due to battery dumping		3	1	3
Habitat destruction due to land requirements		3	1	3
Large scale contamination of soil/groundwater by waste engine oil		3	2	6
Soil/groundwater contamination due to petroleum fuel spills on land		3	2	6
Sea contamination due to petroleum fuel spills during delivery		5	1	5
Local air pollution due to engine exhausts		2	2	4
Noise pollution due to plant operation		1	2	2

B2-5 Risk results for the PV-wind-battery systems to supply the moderately constrained load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		3	4	12
Premature turbine failure due to corrosion in marine environment		3	3	9
	Technical issues			
Problem of space limitations for wind turbines		1	5	5
Problem of space limitations for PV panel installations				∞
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	4	12
	Cost issues			
Continuous financing problems		4	2	8
Difficulties in finding initial investment due to high initial cost				∞
Resource Security Risks				
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		5	1	5
Solar resource problems due to a prolong period(say two weeks) of no sun		3	2	6
Wind resource problems due to prolong period(two months) of missing power winds		3	2	6
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6
Soil/groundwater contamination due to battery spillages		3	3	9
Soil/groundwater contamination due to battery dumping		3	3	9
Habitat destruction due to land requirements		3	2	6
Noise pollution due to plant operation		1	1	1

B2-6 Risk results for the wind-battery systems to supply the moderately constrained load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature turbine failure due to corrosion in marine environment		3	4	12
	Technical issues			
Problem of space limitations for wind turbines				∞
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	4	12
	Cost issues			

Continuous financing problems	1	4	4
Difficulties in finding initial investment due to high initial cost			∞
Resource Security Risks			
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil	4	5	20
Damage of plant due to natural disasters	4	1	4
Wind resource problems due to two months period of missing power winds	4	2	8
Environmental Problem Risks			
Accumulation of old machinery, excl. batteries	3	2	6
Soil/groundwater contamination due to battery spillages	3	3	9
Soil/groundwater contamination due to battery dumping	3	3	9
Habitat destruction due to land requirements	3	2	6
Noise pollution due to plant operation	1	1	1

B2-7 Risk results for the wind-diesel-battery systems to supply the moderately constrained load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature turbine failure due to corrosion in marine environment		3	4	12
	Technical issues			
Problem of space limitations for wind turbines		1	5	5
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	4	12
	Cost issues			
Continuous financing problems		1	1	1
Difficulties in finding initial investment due to high initial cost		1	3	3
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		2	5	10
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		3	1	3
Wind resource problems due to prolong periods(two months) of missing power winds		2	2	4
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6
Soil/groundwater contamination due to battery spillages		3	2	6
Soil/groundwater contamination due to battery dumping		3	2	6
Habitat destruction due to land requirements		3	1	3
Large scale contamination of soil/groundwater by waste engine oil		3	1	3

Soil/groundwater contamination due to petroleum fuel spills on land	3	1	3
Sea contamination due to petroleum fuel spills during delivery	3	1	3
Local air pollution due to engine exhausts	3	2	6
Noise pollution due to plant operation	1	2	2

B2-8 Risk results for the wind-PV-diesel systems to supply the moderately constrained load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		-	-	-
Premature turbine failure due to corrosion in marine environment		3	4	12
	Technical issues			
Problem of space limitations for wind turbines		1	4	4
Problem of space limitations for PV panel installations		-	-	-
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	4	12
	Cost issues			
Continuous financing problems		4	2	8
Difficulties in finding initial investment due to high initial cost		5	2	10
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		3	5	15
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		4	1	4
Solar resource problems due to a prolong period(say two weeks) of no sun		-	-	
Wind resource problems due to prolong periods(two months) of missing power winds		2	2	4
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6
Habitat destruction due to land requirements		3	1	3
Large scale contamination of soil/groundwater by waste engine oil		3	2	6
Soil/groundwater contamination due to petroleum fuel spills on land		3	2	6
Sea contamination due to petroleum fuel spills during delivery		5	2	10
Local air pollution due to engine exhausts		3	2	6
Noise pollution due to plant operation		1	2	2

B2-9Risk results for the wind-PV-diesel-battery systems to supply the moderately constrained load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		-	-	
Premature turbine failure due to corrosion in marine environment		3	4	12
	Technical issues			
Problem of space limitations for wind turbines		1	5	5
Problem of space limitations for PV panel installations		-	-	
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	4	12
	Cost issues			
Continuous financing problems		4	1	4
Difficulties in finding initial investment due to high initial cost		5	3	15
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		2	5	10
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		4	1	4
Solar resource problems due to a prolong period(say two weeks) of no sun		-	-	
Wind resource problems due to prolong periods(two months) period of missing power winds		2	2	4
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6
Soil/groundwater contamination due to battery spillages		3	2	6
Soil/groundwater contamination due to battery dumping		3	2	6
Habitat destruction due to land requirements		3	1	3
Large scale contamination of soil/groundwater by waste engine oil		3	2	6
Soil/groundwater contamination due to petroleum fuel spills on land		3	2	6
Sea contamination due to petroleum fuel spills during delivery		5	2	10
Local air pollution due to engine exhausts		3	2	6
Noise pollution due to plant operation		1	2	2

B3- Risk results for the severely constrained load demand

B3-1 Risk results for the diesel only systems to supply the severely constrained load

Feasibility Risks				
Description		I	P	R
	Application issues			
Repair delays due to long turnaround times		2	3	6
Damage to plant due to improper use		3	1	3
	Cost issues			
Continuous financing problems		4	3	12
Difficulties in finding initial investment due to high initial cost		5	1	5
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		4	5	20
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		3	1	3
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6
Large scale contamination of soil/groundwater by waste engine oil		3	2	6
Soil/groundwater contamination due to petroleum fuel spills on land		3	2	6
Sea contamination due to petroleum fuel spills during delivery		5	2	10
Local air pollution due to engine exhausts		3	2	6
Noise pollution due to plant operation		1	2	2

B3-2 Risk results for the diesel-battery systems to supply the severely constrained load

Feasibility Risks				
Description		I	P	R
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	2	6
	Cost issues			
Continuous financing problems		4	3	12
Difficulties in finding initial investment due to high initial cost		5	1	5
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		4	5	20
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		3	1	3

Environmental Problem Risks			
Accumulation of old machinery, excl. batteries	3	2	6
Large scale contamination of soil/groundwater by waste engine oil	3	2	6
Soil/groundwater contamination due to petroleum fuel spills on land	3	2	6
Sea contamination due to petroleum fuel spills during delivery	5	2	10
Soil/groundwater contamination due to battery spillages	3	2	6
Soil/groundwater contamination due to battery dumping	3	2	6
Local air pollution due to engine exhausts	3	2	6
Noise pollution due to plant operation	1	2	2

B3-3 Risk results for the PV-battery systems to supply the severely constrained load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		3	5	15
	Technical issues			
Problem of space limitations for PV panel installations				∞
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	2	6
	Cost issues			
Continuous financing problems		4	4	16
Difficulties finding initial lender due to high initial investment				∞
Resource Security Risks				
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		4	1	4
Solar resource problems due to a prolong period(say two weeks) of no sun		5	2	10
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	1	3
Soil/groundwater contamination due to battery spillages		3	3	9
Soil/groundwater contamination due to battery dumping		3	3	9
Habitat destruction due to land requirements		3	1	3

B3-4 Risk results for the PV-diesel-battery systems to supply the severely constrained load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			

Premature PV panel failure due to corrosive marine environment		3	3	9
	Technical issues			
Problem of space limitations for PV panel installations		1	2	2
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	4	12
	Cost issues			
Continuous financing problems		4	2	8
Difficulties in finding initial investment due to high initial cost		5	2	10
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		3	5	15
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		3	1	3
Solar resource problems due to a prolong period(say two weeks) of no sun		2	2	4
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6
Soil/groundwater contamination due to battery spillages		3	1	3
Soil/groundwater contamination due to battery dumping		3	1	3
Habitat destruction due to land requirements		-	-	
Large scale contamination of soil/groundwater by waste engine oil		3	2	6
Soil/groundwater contamination due to petroleum fuel spills on land		3	2	6
Sea contamination due to petroleum fuel spills during delivery		5	2	10
Local air pollution due to engine exhausts		3	2	6
Noise pollution due to plant operation		1	2	2

B3-5 Risk results for the PV-wind-battery systems to supply the severely constrained load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		3	3	9
Premature turbine failure due to corrosion in marine environment		3	3	9
	Technical issues			
Problem of space limitations for wind turbines		1	4	4
Problem of space limitations for PV panel installations		1	5	5
	Application issues			
Repair delays due to long turnaround times		2	4	8

Damage to plant due to improper use		3	4	12
	Cost issues			
Continuous financing problems		4	2	8
Difficulties in finding initial investment due to high initial cost		5	5	25
Resource Security Risks				
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		4	1	4
Solar resource problems due to a prolong period(say two weeks) of no sun		3	2	6
Wind resource problems due to prolong period(two months) of missing power winds		3	2	6
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6
Soil/groundwater contamination due to battery spillages		3	2	6
Soil/groundwater contamination due to battery dumping		3	2	6
Habitat destruction due to land requirements		3	1	3
Noise pollution due to plant operation		1	1	1

B3-6 Risk results for the wind-battery systems to supply the severely constrained load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature turbine failure due to corrosion in marine environment		3	4	12
	Technical issues			
Problem of space limitations for wind turbines				∞
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	3	9
	Cost issues			
Continuous financing problems		4	3	12
Difficulties in finding initial investment due to high initial cost		5	4	20
Resource Security Risks				
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		5	1	5
Wind resource problems due to two months period of missing power winds		5	2	10
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6
Soil/groundwater contamination due to battery spillages		3	2	6
Soil/groundwater contamination due to battery dumping		3	2	6
Habitat destruction due to land requirements		3	3	9

Noise pollution due to plant operation	1	1	1

B3-7 Risk results for the wind-diesel-battery systems to supply the severely constrained load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature turbine failure due to corrosion in marine environment		3	2	6
	Technical issues			
Problem of space limitations for wind turbines		1	4	4
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	4	12
	Cost issues			
Continuous financing problems		4	1	4
Difficulties in finding initial investment due to high initial cost		5	2	10
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		3	5	15
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		3	1	3
Wind resource problems due to prolong periods(two months) of missing power winds		2	2	4
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6
Soil/groundwater contamination due to battery spillages		3	2	6
Soil/groundwater contamination due to battery dumping		3	2	6
Habitat destruction due to land requirements		3	1	3
Large scale contamination of soil/groundwater by waste engine oil		3	1	3
Soil/groundwater contamination due to petroleum fuel spills on land		3	1	3
Sea contamination due to petroleum fuel spills during delivery		5	1	5
Local air pollution due to engine exhausts		3	1	3
Noise pollution due to plant operation		1	1	1

B3-8 Risk results for the wind-PV-diesel systems to supply the severely constrained load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		-	-	-

Premature turbine failure due to corrosion in marine environment		3	2	6
	Technical issues			
Problem of space limitations for wind turbines		1	3	3
Problem of space limitations for PV panel installations		-	-	-
	Application issues			
Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	3	9
	Cost issues			
Continuous financing problems		4	2	8
Difficulties in finding initial investment due to high initial cost		5	2	10
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		3	5	15
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		4	1	4
Solar resource problems due to a prolong period(say two weeks) of no sun		-	-	
Wind resource problems due to prolong periods(two months) of missing power winds		2	2	4
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6
Habitat destruction due to land requirements		3	1	3
Large scale contamination of soil/groundwater by waste engine oil		3	1	3
Soil/groundwater contamination due to petroleum fuel spills on land		3	1	3
Sea contamination due to petroleum fuel spills during delivery		5	1	5
Local air pollution due to engine exhausts		3	1	3
Noise pollution due to plant operation		1	1	1

B3-9 Risk results for the wind-PV-diesel-battery systems to supply the severely constrained load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		-	-	-
Premature turbine failure due to corrosion in marine environment		3	3	9
	Technical issues			
Problem of space limitations for wind turbines		1	4	4
Problem of space limitations for PV panel installations		-	-	-
	Application issues			

Repair delays due to long turnaround times		2	4	8
Damage to plant due to improper use		3	4	12
	Cost issues			
Continuous financing problems		4	1	4
Difficulties in finding initial investment due to high initial cost		5	2	10
Resource Security Risks				
System disruptions by 50% petroleum reduction of petroleum product imports		3	5	15
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil		4	5	20
Damage of plant due to natural disasters		4	1	4
Solar resource problems due to a prolong period(say two weeks) of no sun		-	-	
Wind resource problems due to prolong periods(two months) period of missing power winds		3	2	6
Environmental Problem Risks				
Accumulation of old machinery, excl. batteries		3	2	6
Soil/groundwater contamination due to battery spillages		3	2	6
Soil/groundwater contamination due to battery dumping		3	2	6
Habitat destruction due to land requirements		3	1	3
Large scale contamination of soil/groundwater by waste engine oil		3	1	3
Soil/groundwater contamination due to petroleum fuel spills on land		3	1	3
Sea contamination due to petroleum fuel spills during delivery		5	1	5
Local air pollution due to engine exhausts		3	2	6
Noise pollution due to plant operation		1	1	1

B4- Risk Results of the Final System Selected

Table B4-1 shows the risks of the final selected system with minimum renewable energy sources to meet the Essential loads and supplementary diesel generation to cater the present load levels.

B4-1 Risk results for the final selected system to supply the island electric load

Feasibility Risks				
Description		I	P	R
	Fundamental issues			
Premature PV panel failure due to corrosive marine environment		3	5	15
Premature turbine failure due to corrosion in marine environment		3	4	12
	Technical issues			
Problem of space limitations for wind turbines		1	4	4

Problem of space limitations for PV panel installations	1	5	5
Application issues			
Repair delays due to long turnaround times	2	4	8
Damage to plant due to improper use	3	4	12
Cost issues			
Continuous financing problems	4	1	4
Difficulties in finding initial investment due to high initial cost	5	5	25
Resource Security Risks			
System disruptions by 50% petroleum reduction of petroleum product imports	3	5	15
Plant repair difficulties due to 50% reduction of access trips to the island due to peak oil	4	5	20
Damage of plant due to natural disasters	4	1	4
Solar resource problems due to a prolong period(say two weeks) of no sun	2	2	4
Wind resource problems due to prolong periods(two months) period of missing power winds	2	2	4
Environmental Problem Risks			
Accumulation of old machinery, excl. batteries	3	2	6
Soil/groundwater contamination due to battery spillages	3	2	6
Soil/groundwater contamination due to battery dumping	3	2	6
Habitat destruction due to land requirements	3	1	3
Large scale contamination of soil/groundwater by waste engine oil	3	1	3
Soil/groundwater contamination due to petroleum fuel spills on land	3	1	3
Sea contamination due to petroleum fuel spills during delivery	5	1	5
Local air pollution due to engine exhausts	3	1	3
Noise pollution due to plant operation	1	1	1

Appendix C: System Reports (HOMER)

System reports for the present load and load under severe constraint are presented. For all power generation systems presented here considers a sensitivity of 1.2 $/L when diesel generation is involved and with no capacity shortages.

C1: – Systems for Present Load

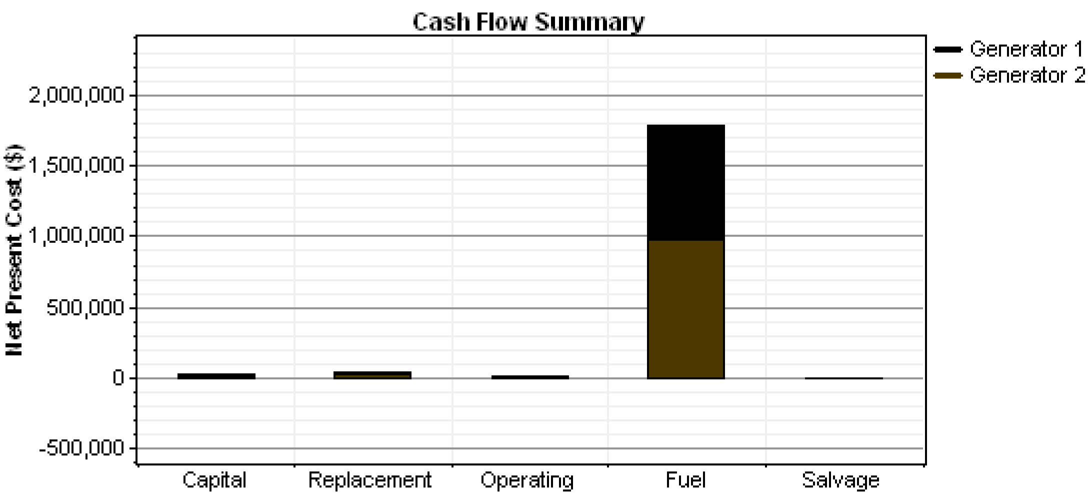
C1-1: System Report - Diesel only

System architecture

Generator 1	41 kW
Generator 2	56 kW

Cost Summary

Total net present cost	$ 1,840,013
Levelized cost of energy	$ 0.447/kWh
Operating cost	$ 142,638/yr

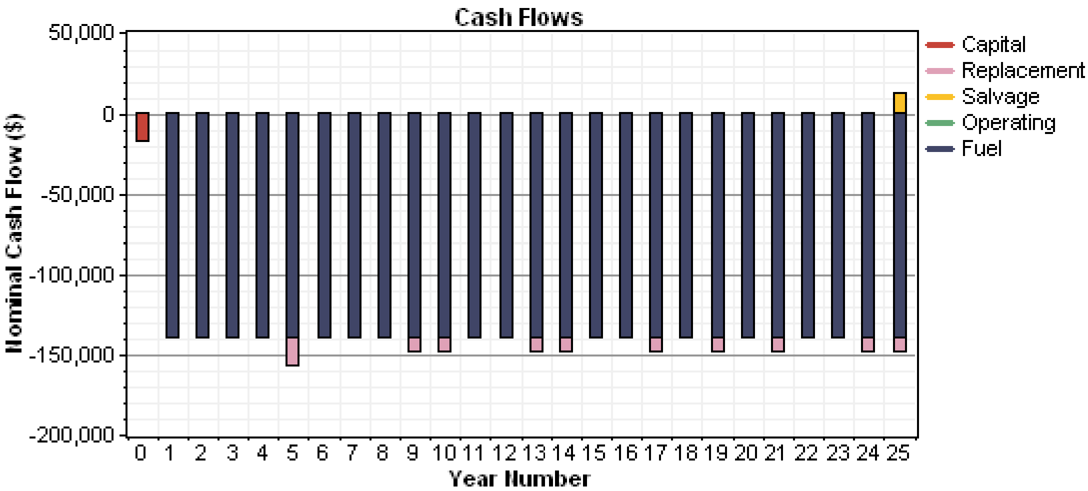


Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)
Generator 1	7,773	21,944	3,120	813,009	-1,628	844,219
Generator 2	8,848	21,105	2,751	964,371	-1,278	995,796
System	16,621	43,049	5,871	1,777,380	-2,906	1,840,015

Annualized Costs

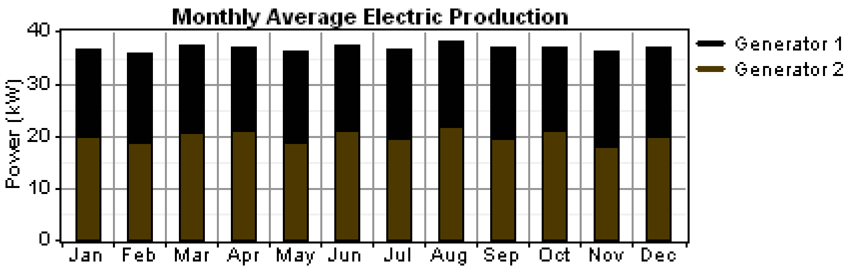
Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
Generator 1	608	1,717	244	63,599	-127	66,040
Generator 2	692	1,651	215	75,440	-100	77,898
System	1,300	3,368	459	139,039	-227	143,938



Electrical

Component	Production	Fraction
	(kWh/yr)	
Generator 1	147,958	46%
Generator 2	174,337	54%
Total	322,295	100%

Quantity	Value	Units
Excess electricity	0.000668	kWh/yr
Unmet load	0.000809	kWh/yr
Capacity shortage	0.00	kWh/yr
Renewable fraction	0.000	

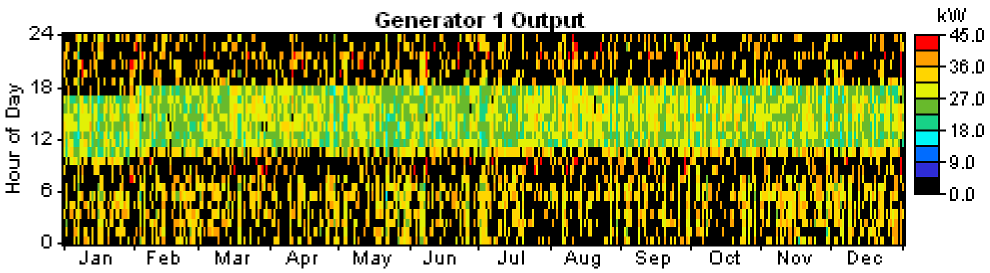


Generator 1

Quantity	Value	Units
Hours of operation	4,881	hr/yr
Number of starts	1,261	starts/yr
Operational life	4.10	yr
Capacity factor	41.2	%
Fixed generation cost	4.37	$/hr
Marginal generation cost	0.300	$/kWhyr

Quantity	Value	Units
Electrical production	147,958	kWh/yr
Mean electrical output	30.3	kW
Min. electrical output	14.3	kW
Max. electrical output	41.0	kW

Quantity	Value	Units
Fuel consumption	52,999	L/yr
Specific fuel consumption	0.358	L/kWh
Fuel energy input	521,512	kWh/yr
Mean electrical efficiency	28.4	%

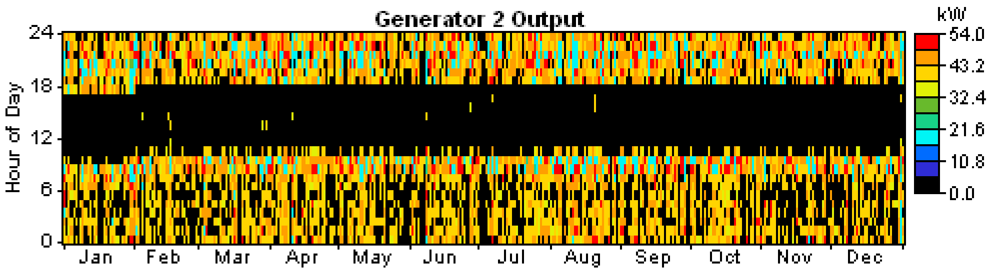


Generator 2

Quantity	Value	Units
Hours of operation	4,304	hr/yr
Number of starts	1,052	starts/yr
Operational life	4.65	yr
Capacity factor	35.5	%
Fixed generation cost	5.87	$/hr
Marginal generation cost	0.300	$/kWhyr

Quantity	Value	Units
Electrical production	174,337	kWh/yr
Mean electrical output	40.5	kW
Min. electrical output	16.8	kW
Max. electrical output	50.9	kW

Quantity	Value	Units
Fuel consumption	62,866	L/yr
Specific fuel consumption	0.361	L/kWh
Fuel energy input	618,604	kWh/yr
Mean electrical efficiency	28.2	%



Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	305,112
Carbon monoxide	753
Unburned hydocarbons	83.4
Particulate matter	56.8
Sulfur dioxide	613
Nitrogen oxides	6,720

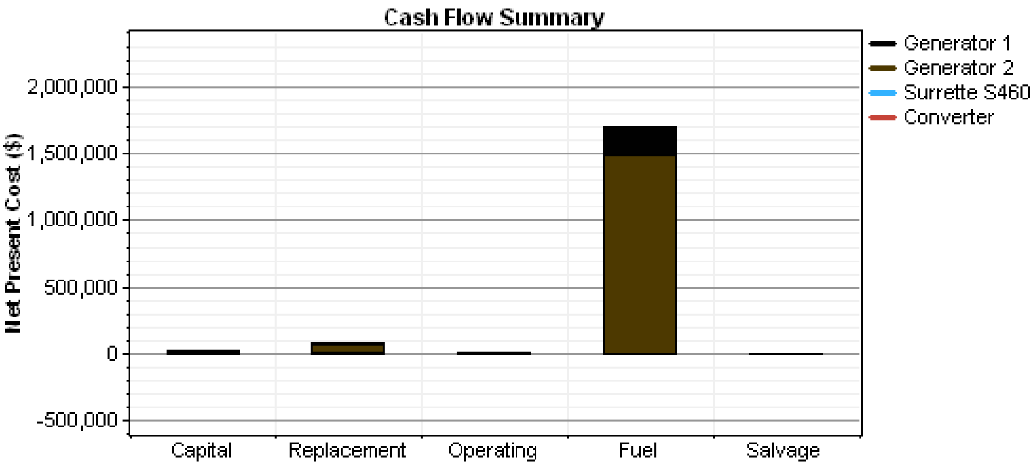
C1-2: System Report - Diesel + Battery Storage

System architecture

Generator 1	13 kW
Generator 2	37 kW
Battery	25 Surrette S460
Inverter	15 kW
Rectifier	15 kW
Dispatch strategy	Cycle Charging

Cost Summary

Total net present cost	$ 1,793,908
Levelized cost of energy	$ 0.436/kWh
Operating cost	$ 138,573yr

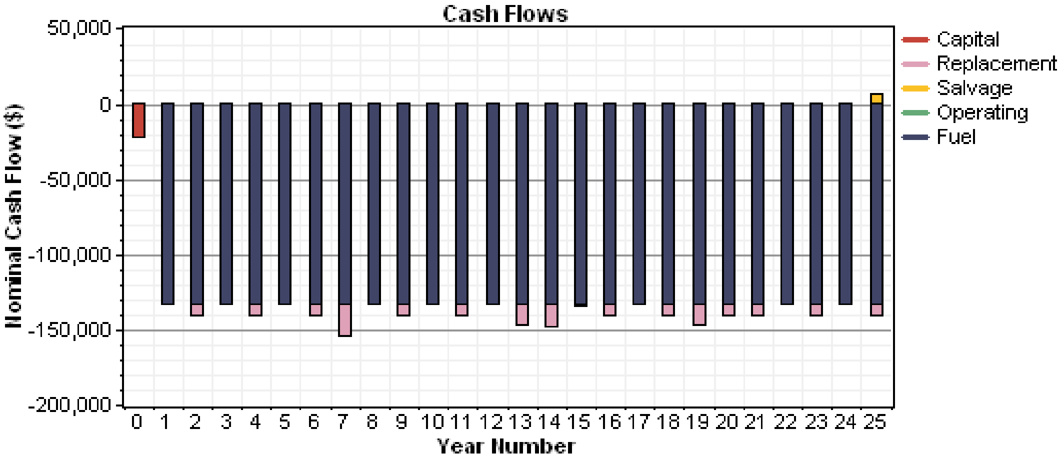


Net Present Costs

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generator 1	5,767	8,668	2,025	208,484	-54	224,891
Generator 2	7,487	53,528	5,568	1,482,811	-837	1,548,556
Surrette S460	7,500	10,982	0	0	-339	18,143
Converter	1,732	723	0	0	-134	2,320
System	22,485	73,901	7,593	1,691,294	-1,365	1,793,910

Annualized Costs

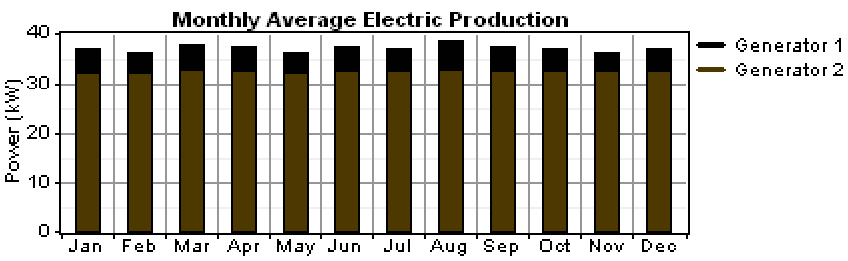
Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
Generator 1	451	678	158	16,309	-4	17,592
Generator 2	586	4,187	436	115,995	-65	121,138
Surrette S460	587	859	0	0	-27	1,419
Converter	135	57	0	0	-11	181
System	1,759	5,781	594	132,304	-107	140,332



Electrical

Component	Production (kWh/yr)	Fraction
Generator 1	41,184	13%
Generator 2	283,493	87%
Total	324,677	100%

Quantity	Value	Units
Excess electricity	0.00274	kWh/yr
Unmet load	85.8	kWh/yr
Capacity shortage	301	kWh/yr
Renewable fraction	0.000	



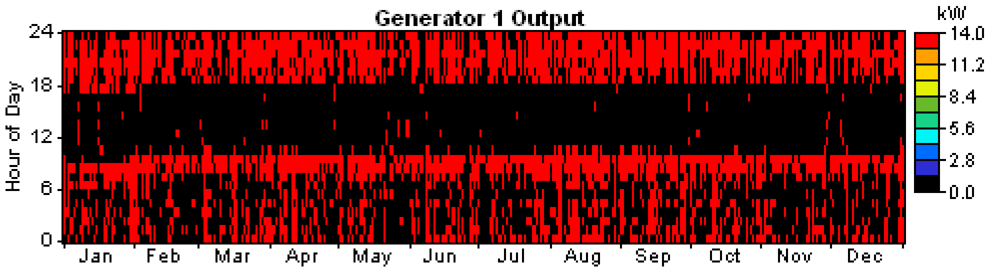
Generator

Quantity	Value	Units
Hours of operation	3,168	hr/yr
Number of starts	1,163	starts/yr

Operational life	6.31	yr
Capacity factor	36.2	%
Fixed generation cost	1.59	$/hr
Marginal generation cost	0.300	$/kWhyr

Quantity	Value	Units
Electrical production	41,184	kWh/yr
Mean electrical output	13.0	kW
Min. electrical output	13.0	kW
Max. electrical output	13.0	kW

Quantity	Value	Units
Fuel consumption	13,591	L/yr
Specific fuel consumption	0.330	L/kWh
Fuel energy input	133,734	kWh/yr
Mean electrical efficiency	30.8	%

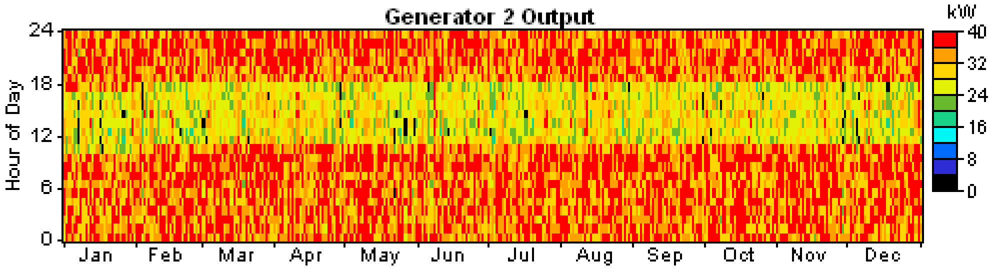


Generator 2

Quantity	Value	Units
Hours of operation	8,712	hr/yr
Number of starts	39	starts/yr
Operational life	1.72	yr
Capacity factor	87.5	%
Fixed generation cost	4.10	$/hr
Marginal generation cost	0.300	$/kWhyr

Quantity	Value	Units
Electrical production	283,493	kWh/yr
Mean electrical output	32.5	kW
Min. electrical output	19.1	kW
Max. electrical output	37.0	kW

Quantity	Value	Units
Fuel consumption	96,663	L/yr
Specific fuel consumption	0.341	L/kWh
Fuel energy input	951,162	kWh/yr
Mean electrical efficiency	29.8	%

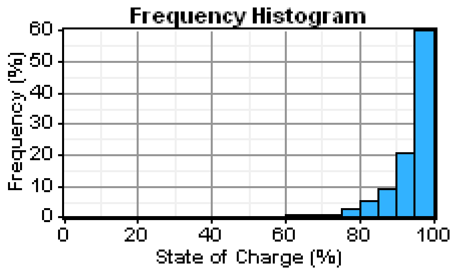


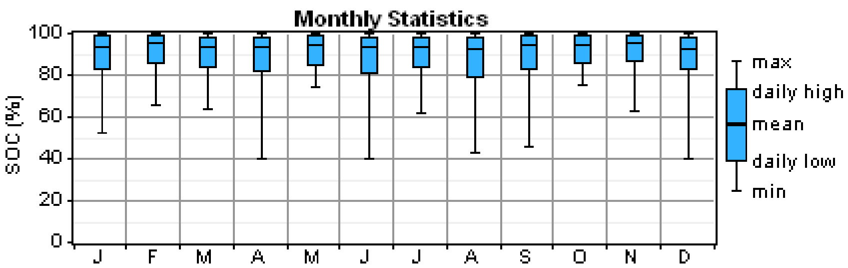
Battery

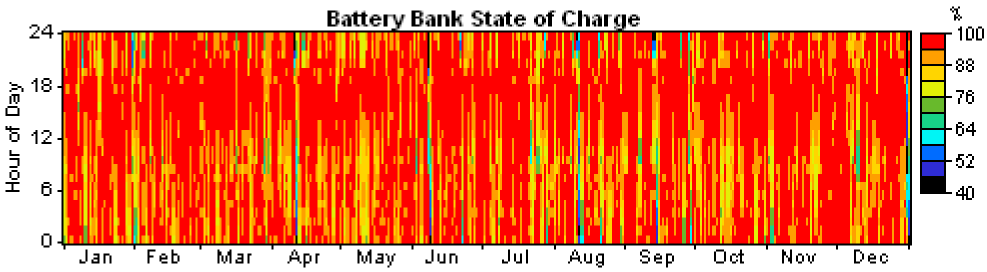
Quantity	Value
String size	1
Strings in parallel	25
Batteries	25
Bus voltage (V)	6

Quantity	Value	Units
Nominal capacity	69.0	kWh
Usable nominal capacity	41.4	kWh
Autonomy	1.13	hr
Lifetime throughput	34,850	kWh
Battery wear cost	0.241	$/kWh
Average energy cost	0.441	$/kWh

Quantity	Value	Units
Energy in	5,929	kWh/yr
Energy out	4,745	kWh/yr
Storage depletion	2.99	kWh/yr
Losses	1,180	kWh/yr
Annual throughput	5,306	kWh/yr
Expected life	6.57	yr



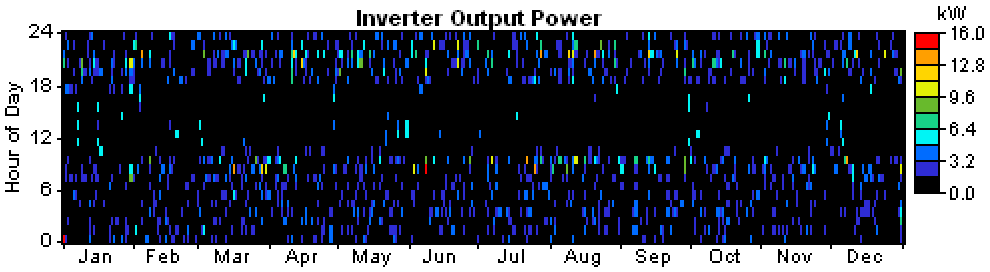


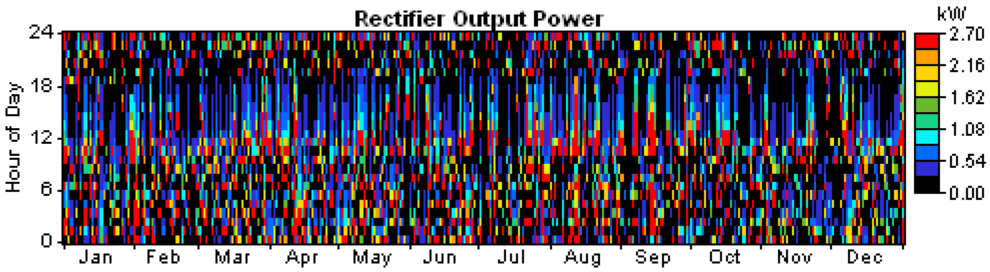


Converter

Quantity	Inverter	Rectifier	Units
Capacity	15.0	15.0	kW
Mean output	0.5	0.7	kW
Minimum output	0.0	0.0	kW
Maximum output	15.0	2.7	kW
Capacity factor	3.4	4.5	%

Quantity	Inverter	Rectifier	Units
Hours of operation	1,893	6,863	hrs/yr
Energy in	4,745	6,975	kWh/yr
Energy out	4,508	5,929	kWh/yr
Losses	237	1,046	kWh/yr





Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	290,334
Carbon monoxide	717
Unburned hydocarbons	79.4
Particulate matter	54
Sulfur dioxide	583
Nitrogen oxides	6,395

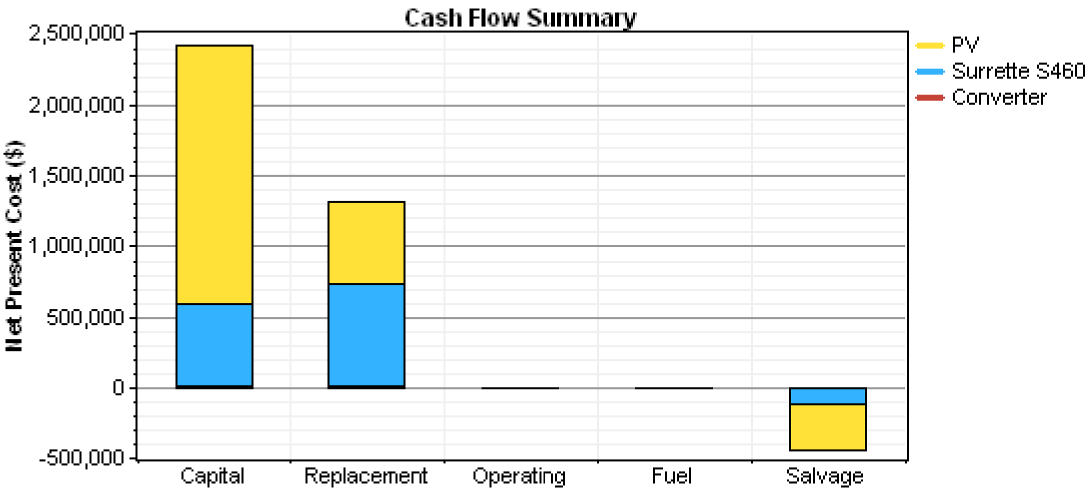
C1-3: System Report – PV + Battery Storage

System architecture

PV Array	305 kW
Battery	1,920 Surrette S460
Inverter	75 kW
Rectifier	75 kW

Cost summary

Total net present cost	$ 3,281,467
Levelized cost of energy	$ 0.797/kWh
Operating cost	$ 67,802/yr

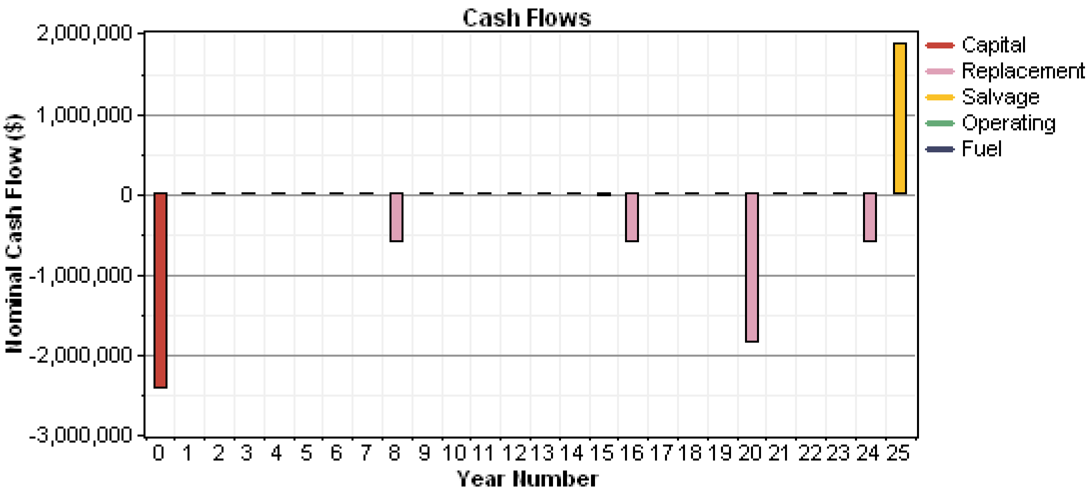


Net Present Costs

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	1,830,000	570,603	0	0	-319,791	2,080,812
Surrette S460	576,000	730,390	0	0	-117,431	1,188,959
Converter	8,732	3,643	0	0	-678	11,697
System	2,414,732	1,304,637	0	0	-437,901	3,281,468

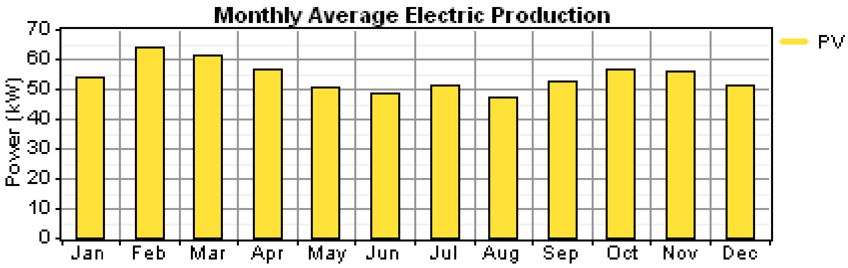
Annualized Costs

Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	143,155	44,636	0	0	-25,016	162,775
Surrette S460	45,059	57,136	0	0	-9,186	93,008
Converter	683	285	0	0	-53	915
System	188,897	102,057	0	0	-34,256	256,698



Electrical

Component	Production (kWh/yr)	Fraction
PV array	474,290	100%
Total	474,290	100%



Load	Consumption (kWh/yr)	Fraction
AC primary load	322,028	100%
Total	322,028	100%

Quantity	Value	Units

Excess electricity	84,655	kWh/yr
Unmet load	268	kWh/yr
Capacity shortage	319	kWh/yr
Renewable fraction	1.000	

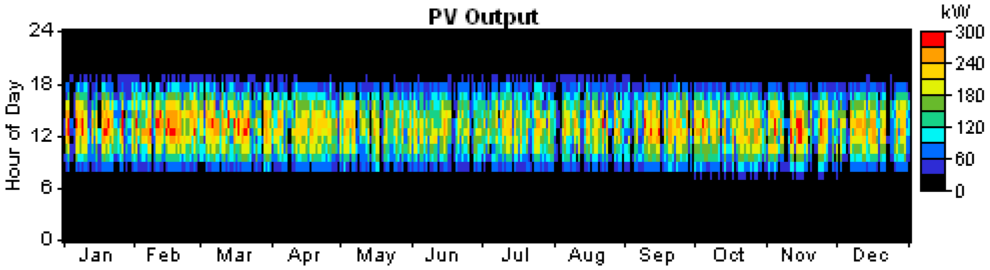
PV

Quantity	Value	Units
Rated capacity	305	kW

Mean output	54.1	kW
Mean output	1,299	kWh/d
Capacity factor	17.8	%
Total production	474,290	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	296	kW

PV penetration	147	%
Hours of operation	4,380	hr/yr
Levelized cost	0.343	$/kWh

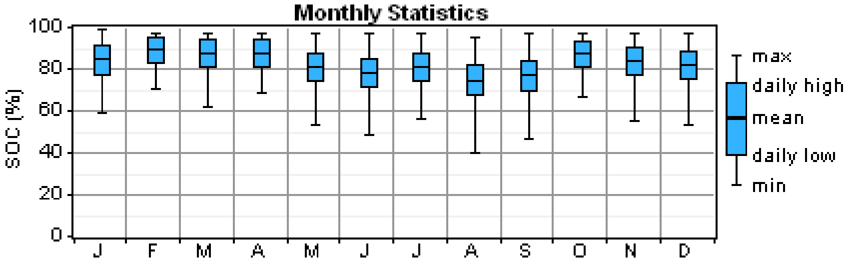


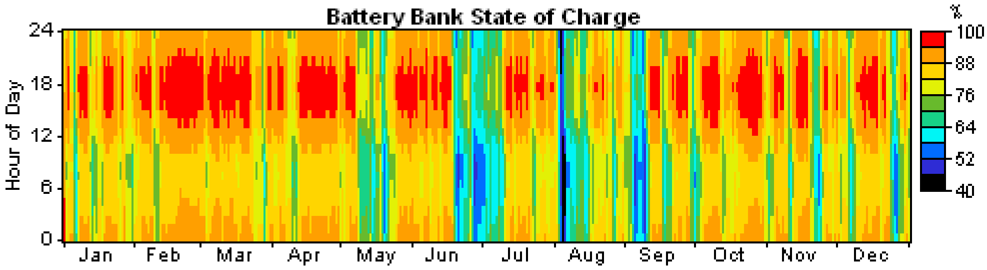
Battery

Quantity	Value
String size	1
Strings in parallel	1,920
Batteries	1,920
Bus voltage (V)	6

Quantity	Value	Units
Nominal capacity	5,299	kWh
Usable nominal capacity	3,180	kWh
Autonomy	86.4	hr
Lifetime throughput	2,676,480	kWh
Battery wear cost	0.241	$/kWh
Average energy cost	0.000	$/kWh

Quantity	Value	Units
Energy in	259,330	kWh/yr
Energy out	208,671	kWh/yr
Storage depletion	1,382	kWh/yr
Losses	49,277	kWh/yr
Annual throughput	233,301	kWh/yr
Expected life	8.00	yr

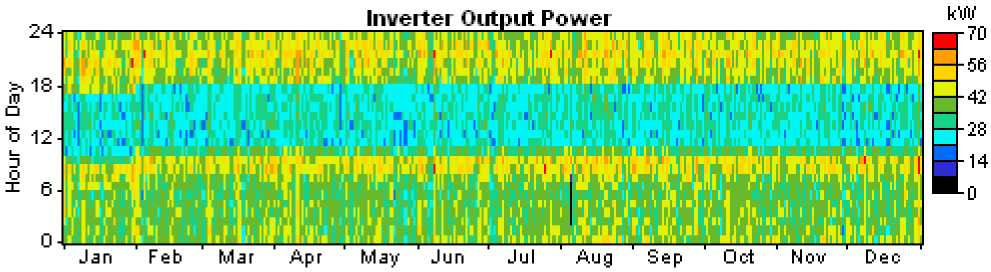


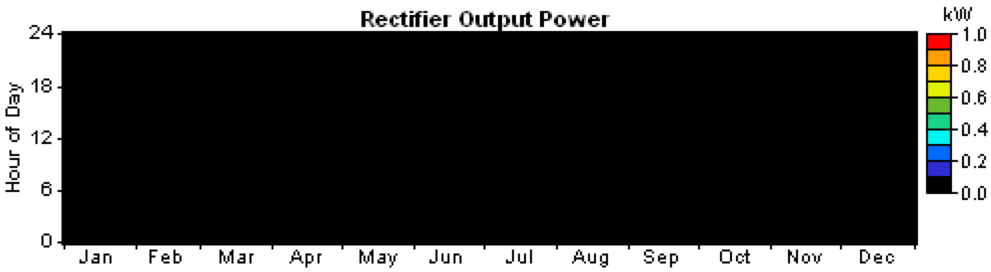


Converter

Quantity	Inverter	Rectifier	Units
Capacity	75.0	75.0	kW
Mean output	36.8	0.0	kW
Minimum output	0.0	0.0	kW
Maximum output	68.2	0.0	kW
Capacity	49.0	0.0	%

factor			
Quantity	**Inverter**	**Rectifier**	**Units**
Hours of operation	8,755	0	hrs/yr
Energy in	338,976	0	kWh/yr
Energy out	322,028	0	kWh/yr
Losses	16,948	0	kWh/yr





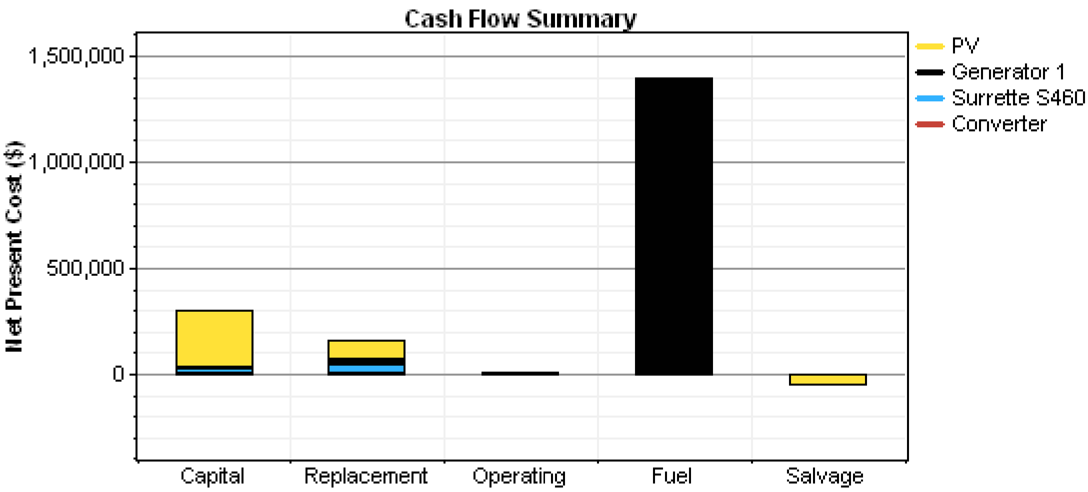
C1-4: System Report - PV + Diesel + Battery Storage

System architecture

PV Array	45 kW
Generator 1	45 kW
Battery	65 Surrette S460
Inverter	45 kW
Rectifier	45 kW
Dispatch strategy	Cycle Charging

Cost summary

Total net present cost	$ 1,805,372
Levelized cost of energy	$ 0.438/kWh
Operating cost	$ 117,542/yr



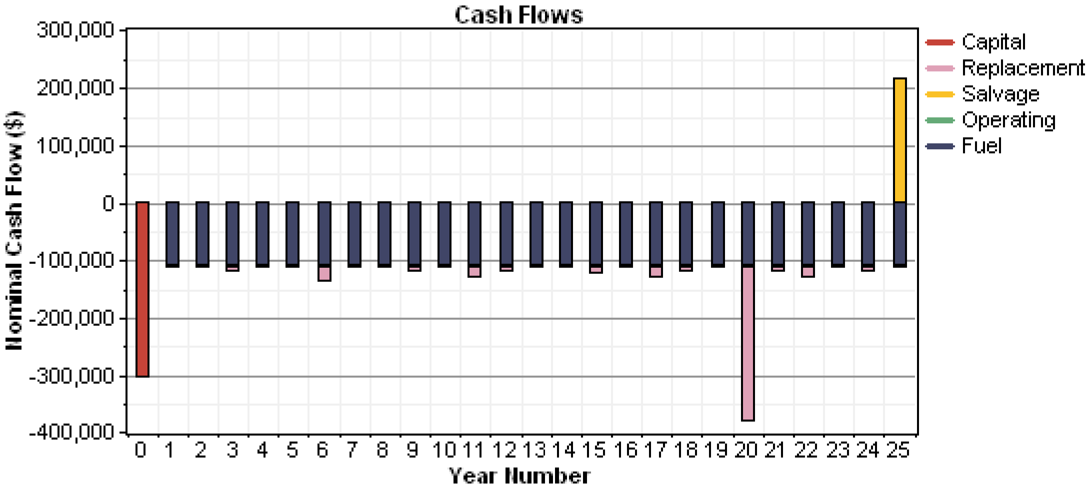
Net Present Costs

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	270,000	84,187	0	0	-47,182	307,005
Generator 1	8,060	32,342	4,384	1,392,036	-800	1,436,021
Surrette S460	19,500	37,627	0	0	-1,789	55,338
Converter	5,232	2,183	0	0	-406	7,008
System	302,791	156,340	4,384	1,392,036	-50,178	1,805,372

Annualized Costs

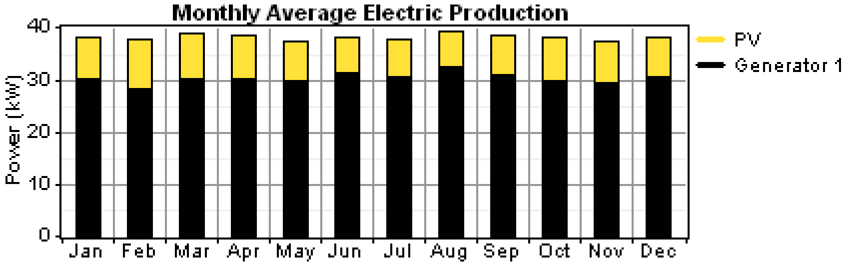
Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	21,121	6,586	0	0	-3,691	24,016
Generator 1	630	2,530	343	108,894	-63	112,335

Surrette S460	1,525	2,943	0	0	-140	4,329
Converter	409	171	0	0	-32	548
System	23,686	12,230	343	108,894	-3,925	141,228



Electrical

Component	Production	Fraction
	(kWh/yr)	
PV array	69,977	21%
Generator 1	264,201	79%
Total	334,179	100%



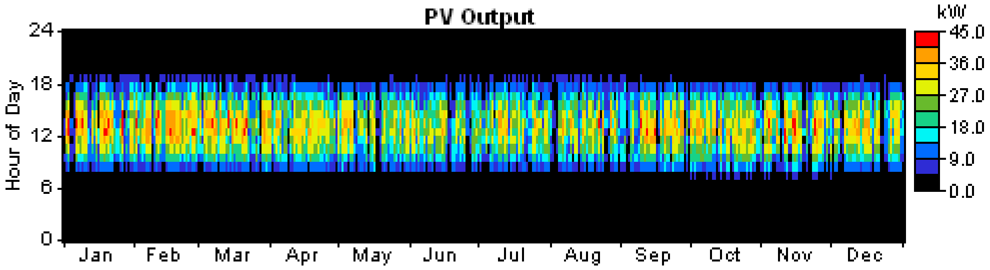
Load	Consumption	Fraction
	(kWh/yr)	
AC primary load	322,226	100%
Total	322,226	100%

Quantity	Value	Units
Excess electricity	2,826	kWh/yr
Unmet load	70.0	kWh/yr
Capacity shortage	175	kWh/yr
Renewable fraction	0.209	

PV

Quantity	Value	Units
Rated capacity	45.0	kW
Mean output	7.99	kW
Mean output	192	kWh/d
Capacity factor	17.8	%
Total production	69,977	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	43.6	kW
PV penetration	21.7	%
Hours of operation	4,380	hr/yr
Levelized cost	0.343	$/kWh

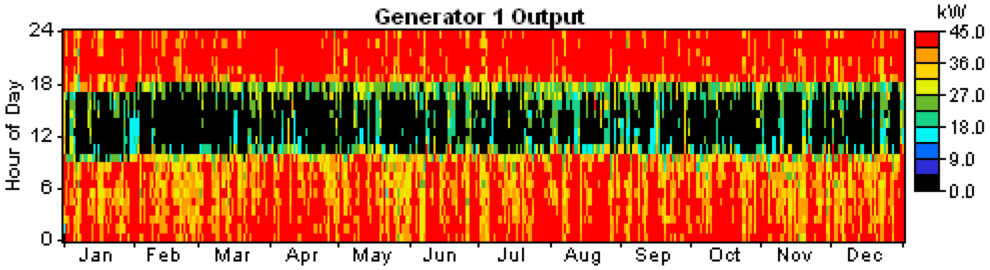


Generator 1

Quantity	Value	Units
Hours of operation	6,859	hr/yr
Number of starts	377	starts/yr
Operational life	2.92	yr
Capacity factor	67.0	%
Fixed generation cost	4.77	$/hr
Marginal generation cost	0.300	$/kWhyr

Quantity	Value	Units
Electrical production	264,201	kWh/yr
Mean electrical output	38.5	kW
Min. electrical output	13.5	kW
Max. electrical output	45.0	kW

Quantity	Value	Units
Fuel consumption	90,745	L/yr
Specific fuel consumption	0.343	L/kWh
Fuel energy input	892,933	kWh/yr
Mean electrical efficiency	29.6	%

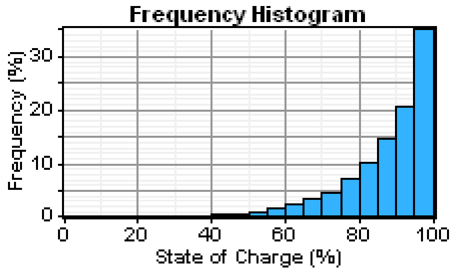


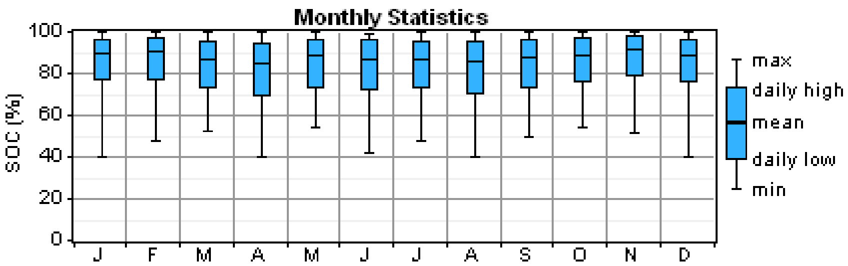
Battery

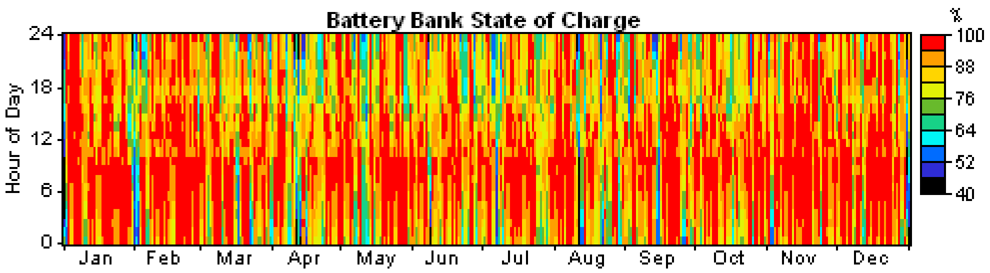
Quantity	Value
String size	1
Strings in parallel	65
Batteries	65
Bus voltage (V)	6

Quantity	Value	Units
Nominal capacity	179	kWh
Usable nominal capacity	108	kWh
Autonomy	2.93	hr
Lifetime throughput	90,610	kWh
Battery wear cost	0.241	$/kWh
Average energy cost	0.350	$/kWh

Quantity	Value	Units
Energy in	18,635	kWh/yr
Energy out	14,932	kWh/yr
Storage depletion	27.2	kWh/yr
Losses	3,676	kWh/yr
Annual throughput	16,695	kWh/yr
Expected life	5.43	yr

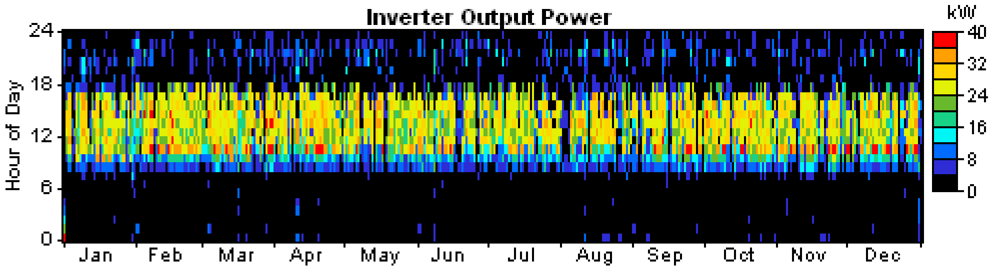


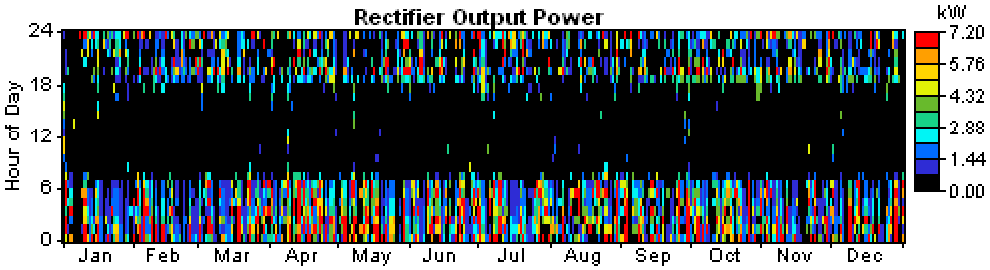




Converter

Quantity	Inverter	Rectifier	Units
Capacity	45.0	45.0	kW
Mean output	8.0	1.1	kW
Minimum output	0.0	0.0	kW
Maximum output	39.9	7.0	kW
Capacity factor	17.7	2.5	%
Hours of operation	4,947	3,809	hrs/yr
Energy in	73,387	11,693	kWh/yr
Energy out	69,718	9,939	kWh/yr
Losses	3,669	1,754	kWh/yr





Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	238,962
Carbon monoxide	590
Unburned hydocarbons	65.3
Particulate matter	44.5
Sulfur dioxide	480
Nitrogen oxides	5,263

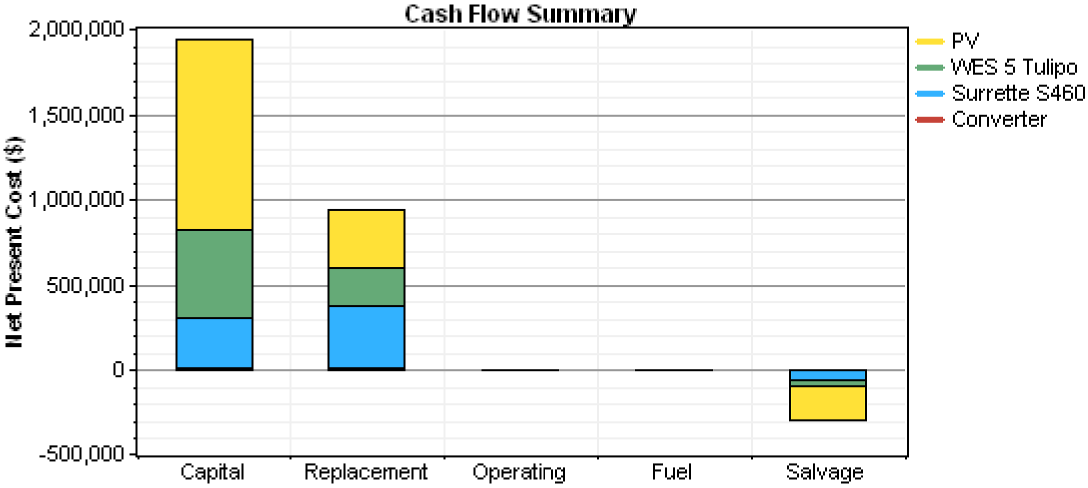
C1-5: System Report – Wind + PV + Battery Storage

System architecture

PV Array	185 kW
Wind turbine	42 WES 5 Tulipo
Battery	975 Surrette S460
Inverter	70 kW
Rectifier	70 kW

Cost summary

Total net present cost	$ 2,580,105
Levelized cost of energy	$ 0.627/kWh
Operating cost	$ 50,414/yr

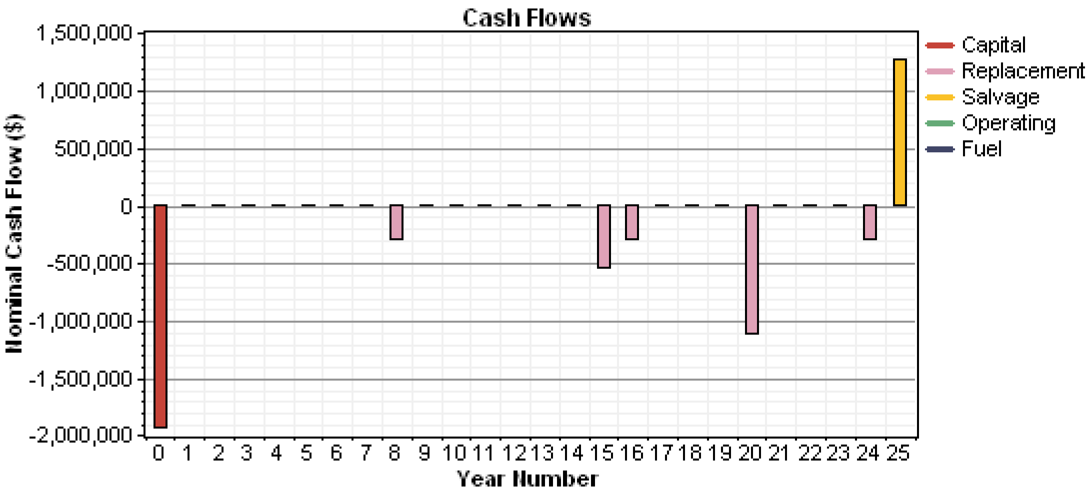


Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)
PV	1,110,000	346,104	0	0	-193,972	1,262,132
WES 5 Tulipo	525,000	219,064	0	0	-40,775	703,290
Surrette S460	292,500	370,901	0	0	-59,633	603,768
Converter	8,148	3,400	0	0	-633	10,916
System	1,935,648	939,469	0	0	-295,012	2,580,105

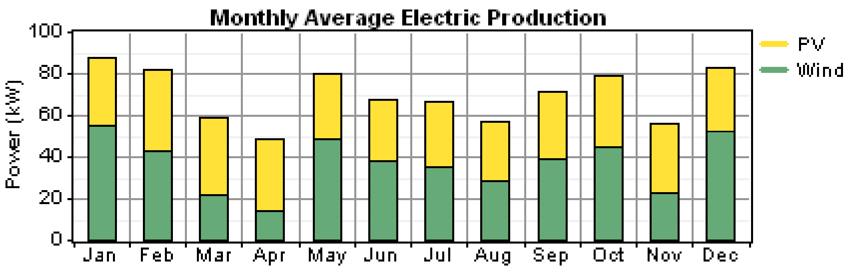
Annualized Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
PV	86,832	27,075	0	0	-15,174	98,732
WES 5 Tulipo	41,069	17,137	0	0	-3,190	55,016
Surrette S460	22,881	29,014	0	0	-4,665	47,231
Converter	637	266	0	0	-50	854
System	151,419	73,492	0	0	-23,078	201,833



Electrical

Component	Production	Fraction
	(kWh/yr)	
PV array	287,685	47%
Wind turbines	323,678	53%
Total	611,362	100%



Load	Consumption	Fraction
	(kWh/yr)	
AC primary load	322,070	100%
Total	322,070	100%

Quantity	Value	Units
Excess electricity	248,061	kWh/yr
Unmet load	226	kWh/yr
Capacity shortage	320	kWh/yr
Renewable fraction	1.000	

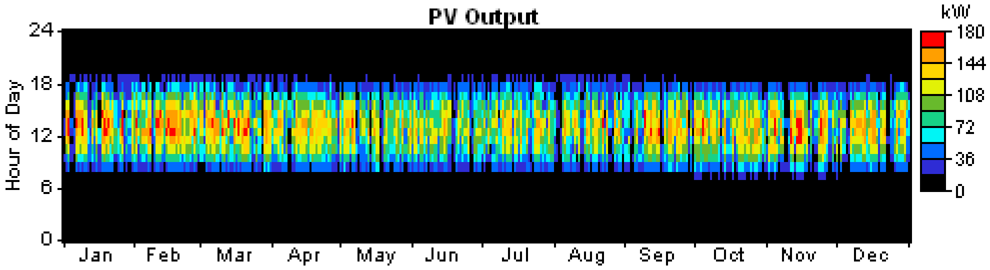
PV

Quantity	Value	Units
Rated capacity	185	kW
Mean output	32.8	kW

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	179	kW
PV penetration	89.3	%

Mean output	788	kWh/d
Capacity factor	17.8	%
Total production	287,685	kWh/yr

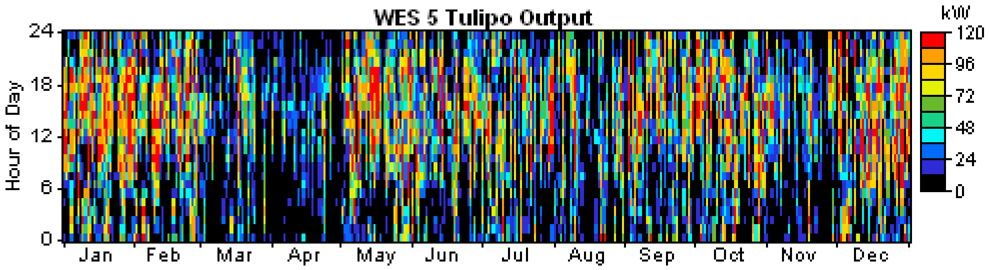
Hours of operation	4,380	hr/yr
Levelized cost	0.343	$/kWh



AC Wind Turbine: WES 5 Tulipo

Variable	Value	Units
Total rated capacity	105	kW
Mean output	36.9	kW
Capacity factor	35.2	%
Total production	323,678	kWh/yr

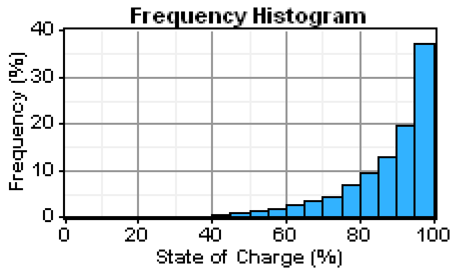
Variable	Value	Units
Minimum output	0.00	kW
Maximum output	110	kW
Wind penetration	100	%
Hours of operation	7,904	hr/yr
Levelized cost	0.170	$/kWh

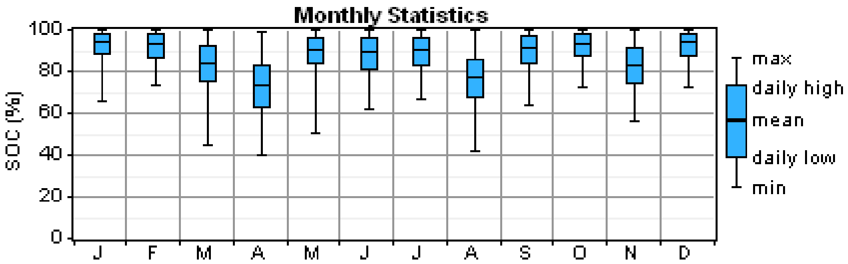


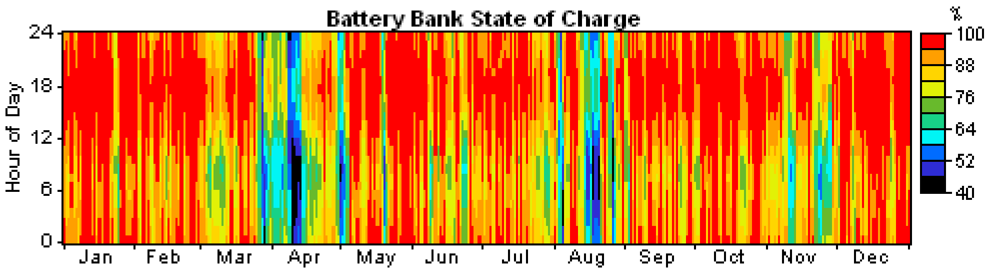
Quantity	Value	Units
Nominal capacity	2,691	kWh
Usable nominal capacity	1,615	kWh
Autonomy	43.9	hr
Lifetime throughput	1,359,150	kWh
Battery wear cost	0.241	$/kWh
Average energy cost	0.000	$/kWh

Quantity	Value	Units
Energy in	143,700	kWh/yr

Energy out	115,036	kWh/yr
Storage depletion	87.6	kWh/yr
Losses	28,576	kWh/yr
Annual throughput	128,615	kWh/yr
Expected life	8.00	yr



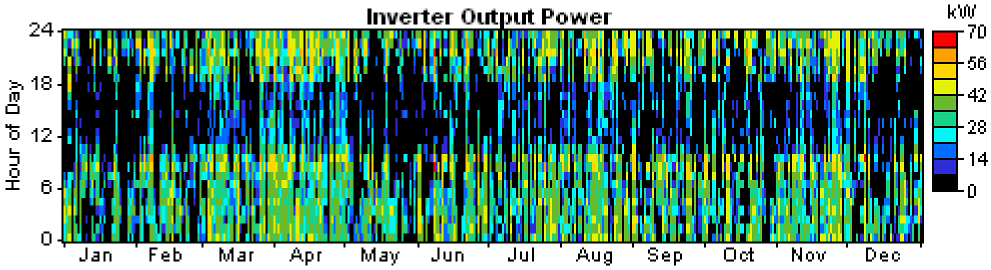


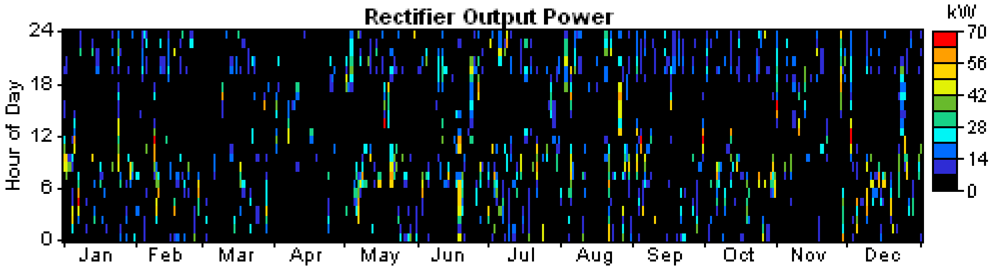


Converter

Quantity	Inverter	Rectifier	Units
Capacity	70.0	70.0	kW
Mean output	16.9	3.1	kW
Minimum output	0.0	0.0	kW
Maximum output	64.8	70.0	kW
Capacity factor	24.1	4.4	%

Quantity	Inverter	Rectifier	Units
Hours of operation	5,332	1,741	hrs/yr
Energy in	155,786	31,863	kWh/yr
Energy out	147,996	27,083	kWh/yr
Losses	7,789	4,779	kWh/yr





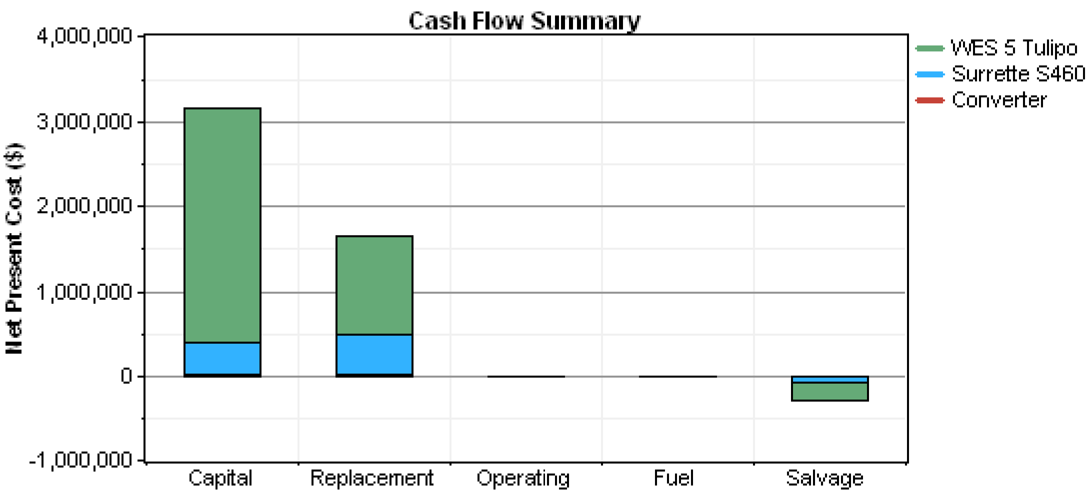
C1-6: System Report – Wind + Battery Storage

System architecture

Wind turbine	220 WES 5 Tulipo
Battery	1,270 Surrette S460
Inverter	140 kW
Rectifier	140 kW

Cost summary

Total net present cost	$ 4,492,199
Levelized cost of energy	$ 1.091/kWh
Operating cost	$ 105,206/yr

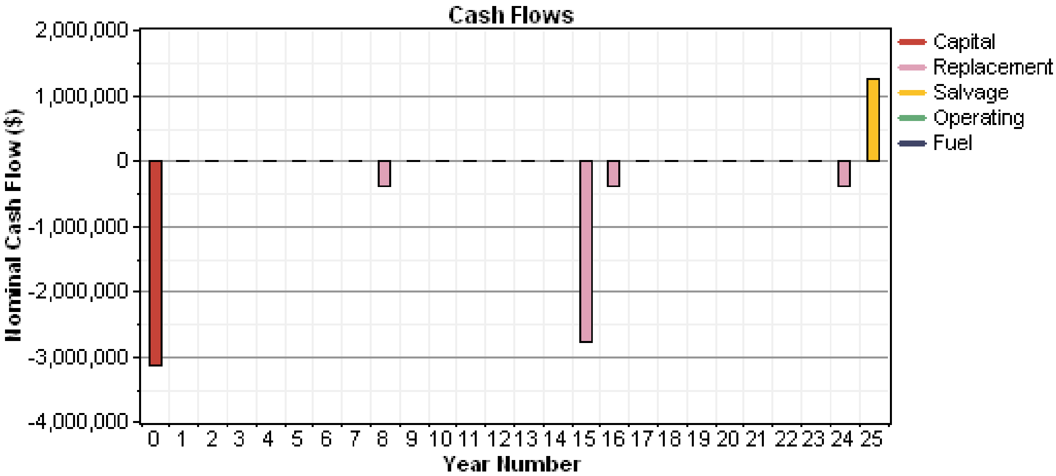


Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)
WES 5 Tulipo	2,750,000	1,147,480	0	0	-213,582	3,683,898
Surrette S460	381,000	483,123	0	0	-77,676	786,447
Converter	16,315	6,808	0	0	-1,267	21,856
System	3,147,315	1,637,410	0	0	-292,526	4,492,200

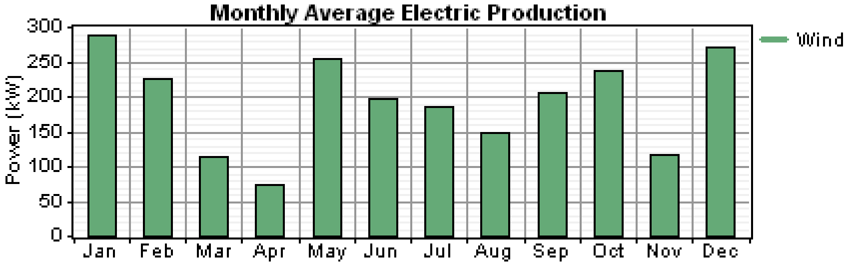
Annualized Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
WES 5 Tulipo	215,123	89,764	0	0	-16,708	288,179
Surrette S460	29,804	37,793	0	0	-6,076	61,521
Converter	1,276	533	0	0	-99	1,710
System	246,204	128,089	0	0	-22,883	351,410



Electrical

Component	Production	Fraction
	(kWh/yr)	
Wind turbines	1,695,455	100%
Total	1,695,455	100%



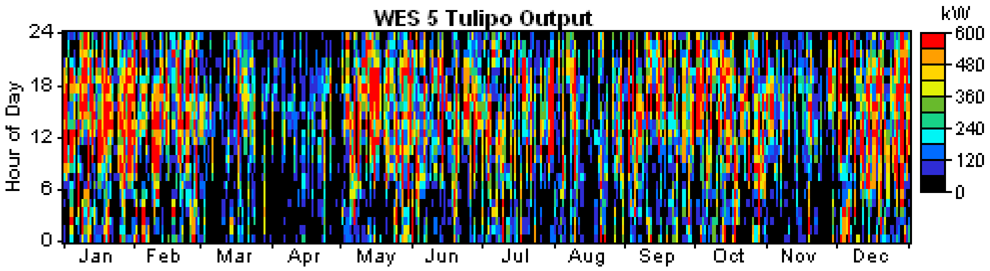
Load	Consumption (kWh/yr)	Fraction
AC primary load	322,105	100%
Total	322,105	100%

Quantity	Value	Units
Excess electricity	1,332,217	kWh/yr
Unmet load	191	kWh/yr
Capacity shortage	319	kWh/yr
Renewable fraction	1.000	

AC Wind Turbine: WES 5 Tulipo

Variable	Value	Units
Total rated capacity	550	kW
Mean output	194	kW
Capacity factor	35.2	%
Total production	1,695,455	kWh/yr

Variable	Value	Units
Minimum output	0.00	kW
Maximum output	577	kW
Wind penetration	526	%
Hours of operation	7,904	hr/yr
Levelized cost	0.170	$/kWh

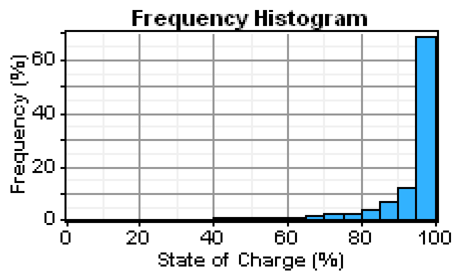


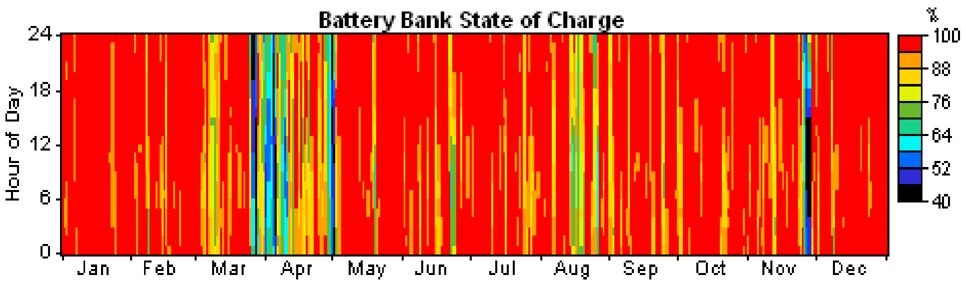
Battery

Quantity	Value
String size	1
Strings in parallel	1,270
Batteries	1,270
Bus voltage (V)	6

Quantity	Value	Units
Nominal capacity	3,505	kWh
Usable nominal capacity	2,103	kWh
Autonomy	57.2	hr
Lifetime throughput	1,770,380	kWh
Battery wear cost	0.241	$/kWh
Average energy cost	0.000	$/kWh

Quantity	Value	Units
Energy in	98,774	kWh/yr
Energy out	79,022	kWh/yr
Storage depletion	3.14	kWh/yr
Losses	19,749	kWh/yr
Annual throughput	88,350	kWh/yr
Expected life	8.00	yr

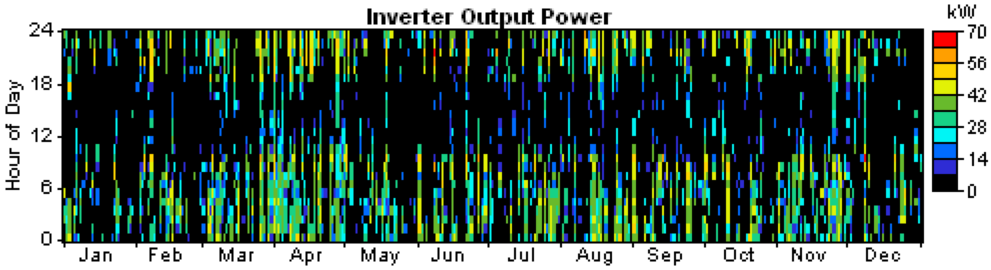


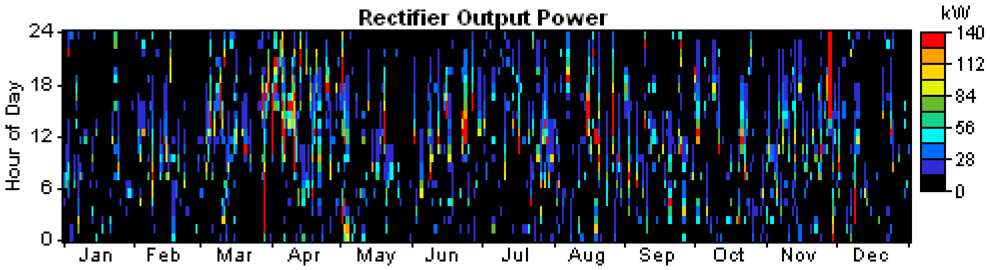


Converter

Quantity	Inverter	Rectifier	Units
Capacity	140	140	kW
Mean output	9	11	kW
Minimum output	0	0	kW
Maximum output	64	137	kW
Capacity factor	6.1	8.1	%

Quantity	Inverter	Rectifier	Units
Hours of operation	2,633	6,120	hrs/yr
Energy in	79,022	116,206	kWh/yr
Energy out	75,071	98,774	kWh/yr
Losses	3,951	17,431	kWh/yr





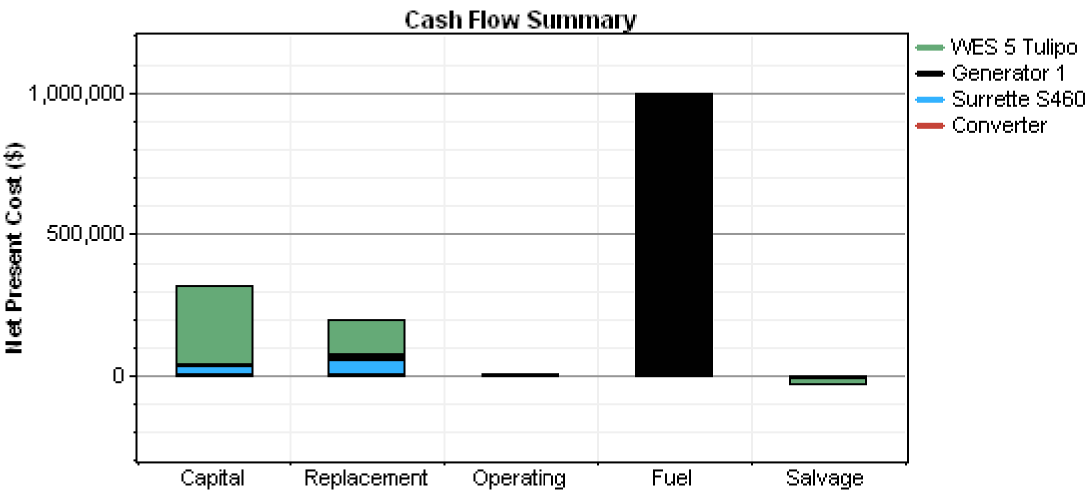
C1-7: - System Report – Wind + Diesel + Battery Storage

System architecture

Wind turbine	22 WES 5 Tulipo
Generator 1	40 kW
Battery	100 Surrette S460
Inverter	35 kW
Rectifier	35 kW
Dispatch strategy	Cycle Charging

Cost summary

Total net present cost	$ 1,478,977
Levelized cost of energy	$ 0.359/kWh
Operating cost	$ 90,916/yr

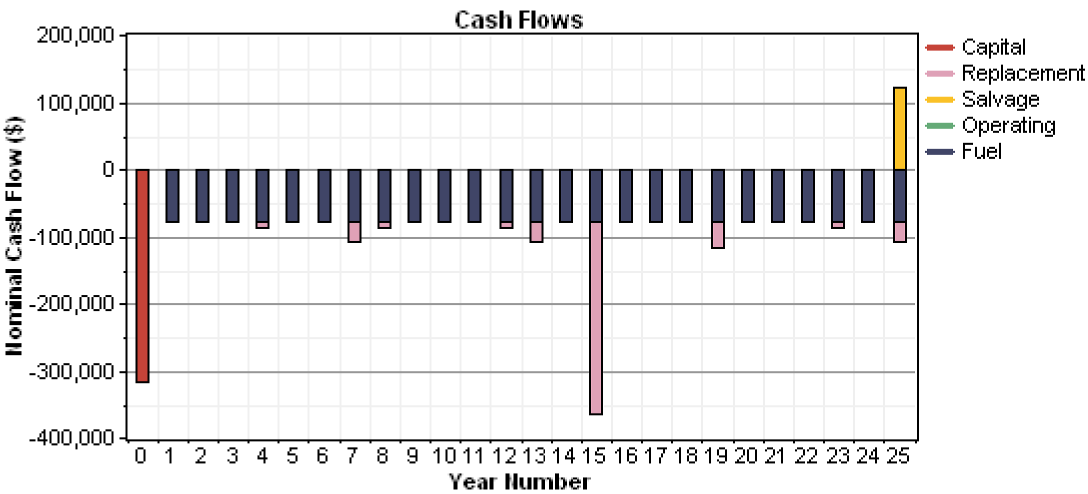


Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)
WES 5 Tulipo	275,000	114,748	0	0	-21,358	368,390
Generator 1	7,701	23,218	3,452	994,102	-446	1,028,027
Surrette S460	30,000	53,380	0	0	-6,265	77,115
Converter	4,065	1,696	0	0	-316	5,445
System	316,767	193,042	3,452	994,102	-28,385	1,478,978

Annualized Costs

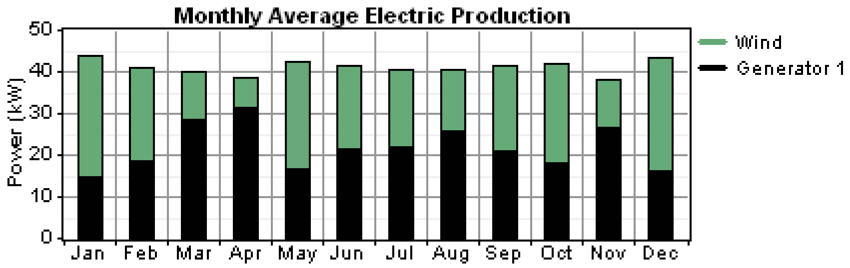
Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
WES 5 Tulipo	21,512	8,976	0	0	-1,671	28,818
Generator 1	602	1,816	270	77,765	-35	80,419
Surrette S460	2,347	4,176	0	0	-490	6,032
Converter	318	133	0	0	-25	426
System	24,780	15,101	270	77,765	-2,220	115,696



Electrical

Component	Production	Fraction
	(kWh/yr)	
Wind turbines	169,545	47%

Generator 1	190,091	53%
Total	359,636	100%



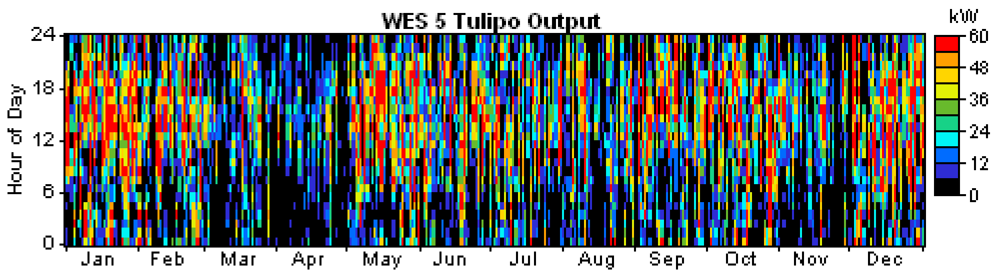
Load	Consumption	Fraction
	(kWh/yr)	
AC primary load	322,268	100%
Total	322,268	100%

Quantity	Value	Units
Excess electricity	26,734	kWh/yr
Unmet load	28.6	kWh/yr
Capacity shortage	76.5	kWh/yr
Renewable fraction	0.471	

AC Wind Turbine: WES 5 Tulipo

Variable	Value	Units
Total rated capacity	55.0	kW
Mean output	19.4	kW
Capacity factor	35.2	%

Variable	Value	Units
Total production	169,545	kWh/yr
Minimum output	0.00	kW
Maximum output	57.7	kW
Wind penetration	52.6	%
Hours of operation	7,904	hr/yr
Levelized cost	0.170	$/kWh



Generator 1

Quantity	Value	Units
Hours of operation	5,401	hr/yr

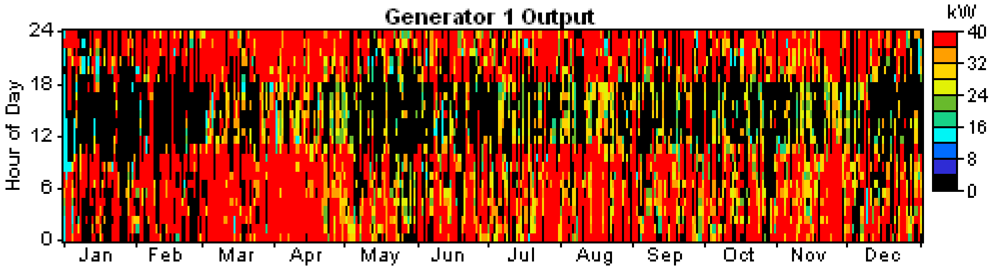
Number of starts	650	starts/yr
Operational life	3.70	yr
Capacity factor	54.2	%

Fixed generation cost	4.28	$/hr
Marginal generation cost	0.300	$/kWhyr

Quantity	Value	Units
Electrical production	190,091	kWh/yr

Quantity	Value	Units
Fuel consumption	64,804	L/yr
Specific fuel consumption	0.341	L/kWh
Fuel energy input	637,676	kWh/yr
Mean electrical efficiency	29.8	%

Mean electrical output	35.2	kW
Min. electrical output	12.0	kW
Max. electrical output	40.0	kW

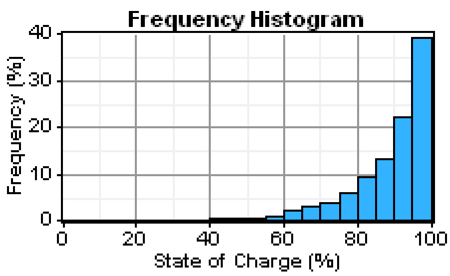


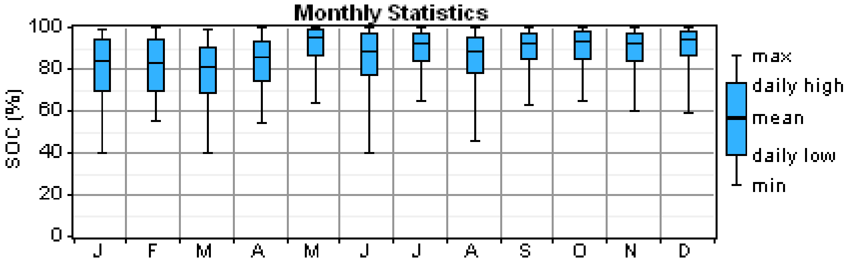
Battery

Quantity	Value
String size	1
Strings in parallel	100
Batteries	100
Bus voltage (V)	6

Quantity	Value	Units
Nominal capacity	276	kWh
Usable nominal capacity	166	kWh
Autonomy	4.50	hr
Lifetime throughput	139,400	kWh
Battery wear cost	0.241	$/kWh
Average energy cost	0.276	$/kWh

Quantity	Value	Units
Energy in	25,566	kWh/yr
Energy out	20,467	kWh/yr
Storage depletion	15.4	kWh/yr
Losses	5,084	kWh/yr
Annual throughput	22,882	kWh/yr
Expected life	6.09	yr

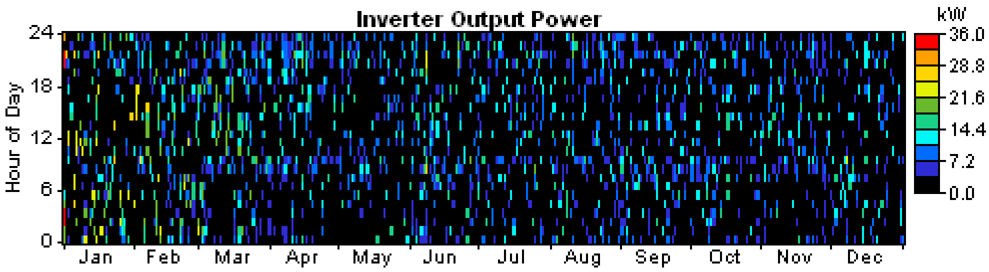


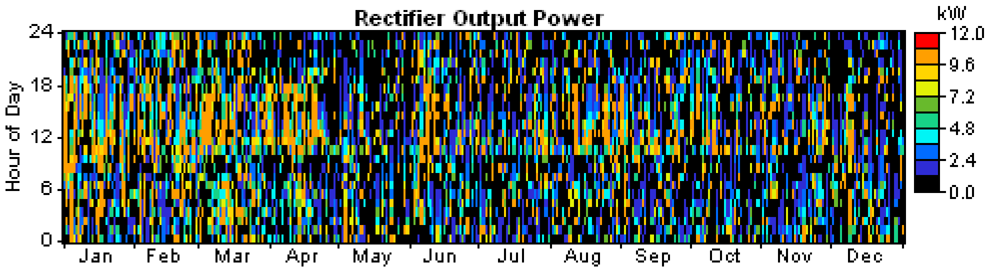


Converter

Quantity	Inverter	Rectifier	Units
Capacity	35.0	35.0	kW
Mean output	2.2	2.9	kW
Minimum output	0.0	0.0	kW
Maximum output	35.0	10.8	kW
Capacity factor	6.3	8.3	%

Quantity	Inverter	Rectifier	Units
Hours of operation	2,592	6,166	hrs/yr
Energy in	20,467	30,078	kWh/yr
Energy out	19,443	25,566	kWh/yr
Losses	1,023	4,511	kWh/yr





Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	170,651
Carbon monoxide	421
Unburned hydocarbons	46.7

Particulate matter	31.8
Sulfur dioxide	343
Nitrogen oxides	3,759

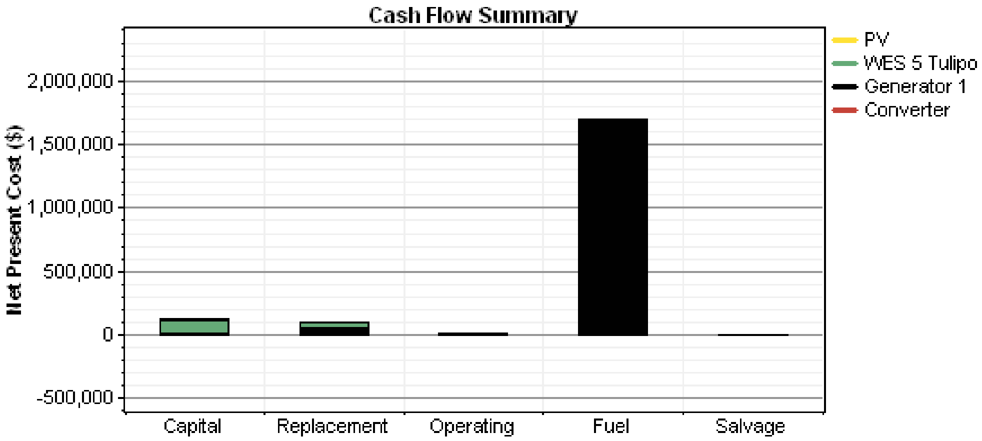
C1- 8: System Report – PV + Wind + Diesel

System architecture

PV Array	1 kW
Wind turbine	8 WES 5 Tulipo
Generator 1	60 kW
Inverter	5 kW
Rectifier	5 kW

Cost summary

Total net present cost	$ 1,888,805
Levelized cost of energy	$ 0.458/kWh
Operating cost	$ 138,704/yr



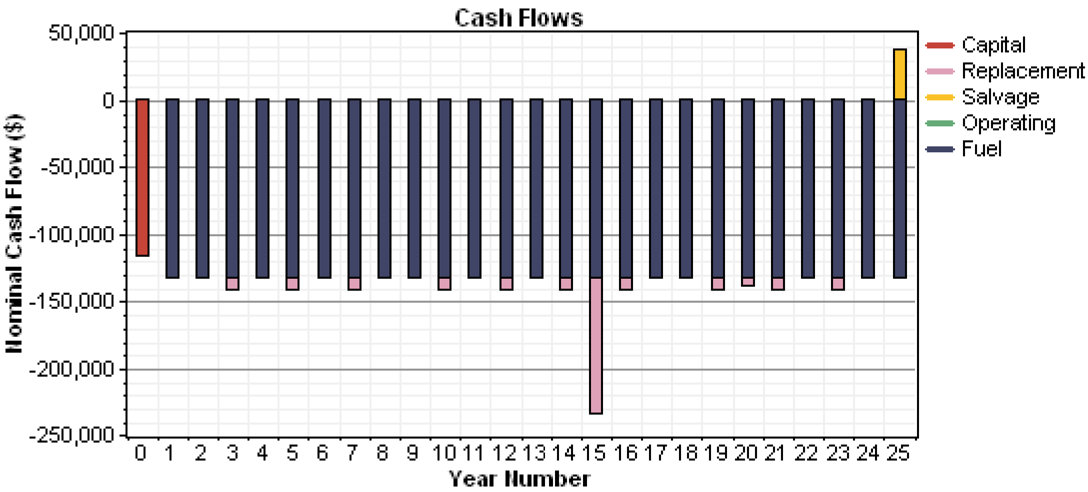
Net Present Costs

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	6,000	1,871	0	0	-1,048	6,822
WES 5 Tulipo	100,000	41,727	0	0	-7,767	133,960
Generator 1	9,134	47,223	5,599	1,685,417	-106	1,747,267
Converter	565	236	0	0	-44	757
System	115,699	91,056	5,599	1,685,417	-8,965	1,888,806

Annualized Costs

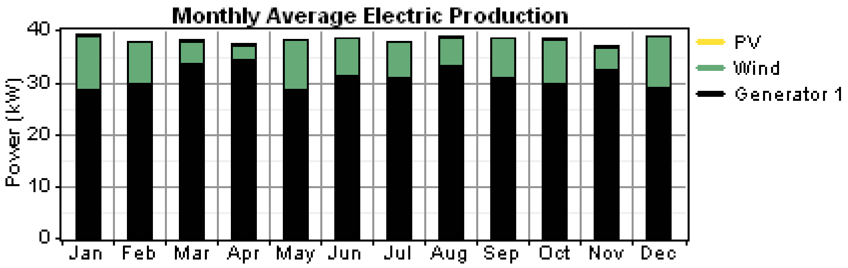
Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	469	146	0	0	-82	534

WES 5 Tulipo	7,823	3,264	0	0	-608	10,479
Generator 1	715	3,694	438	131,845	-8	136,683
Converter	44	18	0	0	-3	59
System	9,051	7,123	438	131,845	-701	147,755



Electrical

Component	Production (kWh/yr)	Fraction
PV array	1,555	0%
Wind turbines	61,653	18%
Generator 1	271,297	81%
Total	334,505	100%



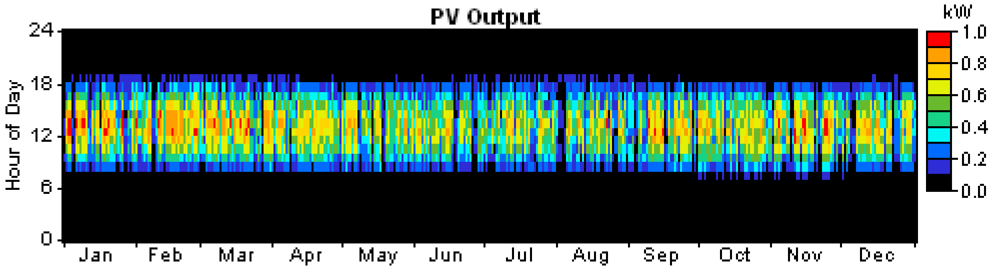
Load	Consumption (kWh/yr)	Fraction
AC primary load	322,270	100%
Total	322,270	100%

Quantity	Value	Units
Excess electricity	12,188	kWh/yr
Unmet load	25.7	kWh/yr
Capacity shortage	265	kWh/yr
Renewable fraction	0.189	

PV

Quantity	Value	Units
Rated capacity	1.00	kW
Mean output	0.178	kW
Mean output	4.26	kWh/d
Capacity factor	17.8	%
Total production	1,555	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	0.970	kW
PV penetration	0.482	%
Hours of operation	4,380	hr/yr
Levelized cost	0.343	$/kWh

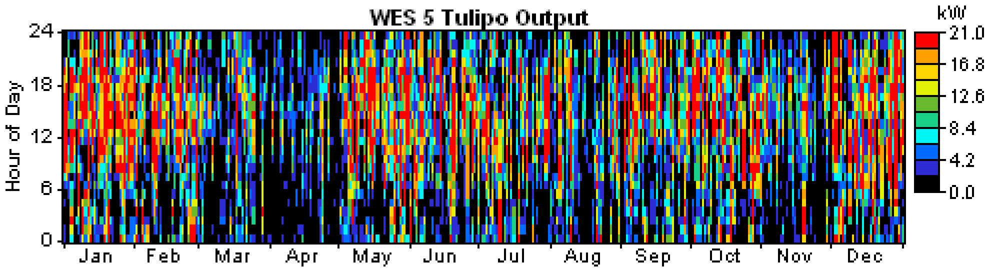


AC Wind Turbine: WES 5 Tulipo

Variable	Value	Units
Total rated capacity	20.0	kW
Mean output	7.04	kW
Capacity factor	35.2	%
Total production	61,653	kWh/yr

Minimum output	0.00	kW
Maximum output	21.0	kW
Wind penetration	19.1	%
Hours of operation	7,904	hr/yr
Levelized cost	0.170	$/kWh

Variable	Value	Units



Generator 1

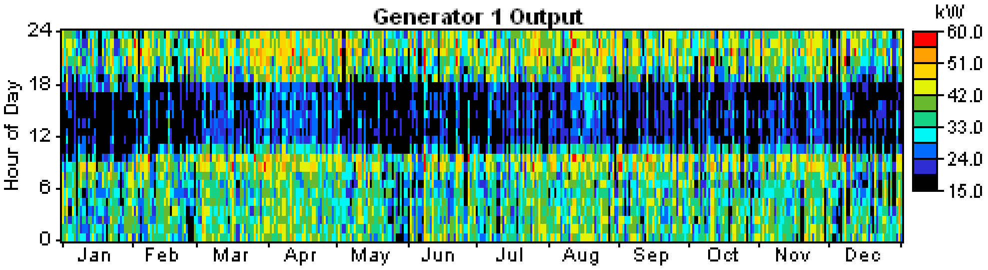
Quantity	Value	Units

Quantity	Value	Units
Electrical production	271,297	kWh/yr
Mean electrical output	31.0	kW

Hours of operation	8,760	hr/yr
Number of starts	1	starts/yr
Operational life	2.28	yr
Capacity factor	51.6	%
Fixed generation cost	6.27	$/hr
Marginal generation cost	0.300	$/kWhyr

Min. electrical output	18.0	kW
Max. electrical output	60.0	kW

Quantity	Value	Units
Fuel consumption	109,870	L/yr
Specific fuel consumption	0.405	L/kWh
Fuel energy input	1,081,125	kWh/yr
Mean electrical efficiency	25.1	%

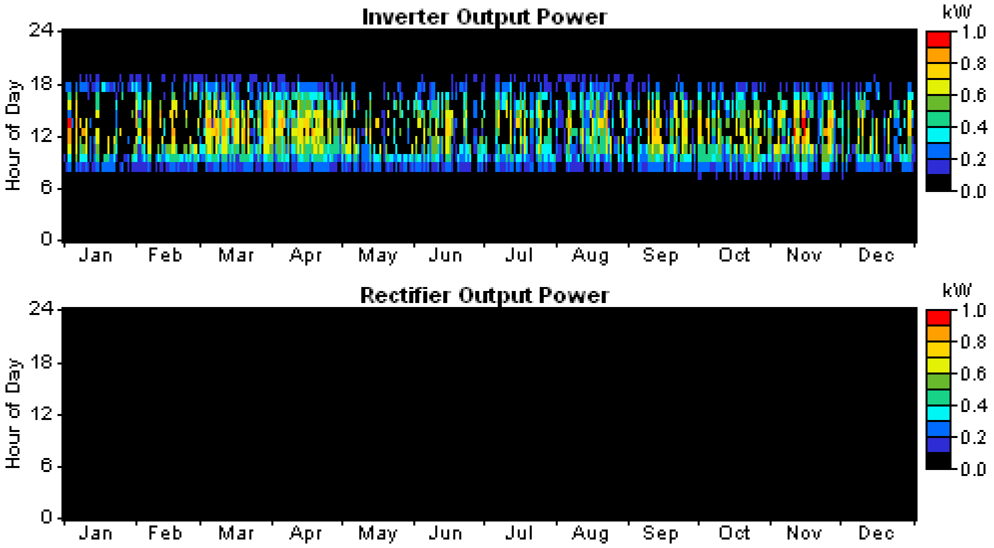


Converter

Quantity	Inverter	Rectifier	Units
Capacity	5.00	5.00	kW
Mean output	0.10	0.00	kW
Minimum output	0.00	0.00	kW
Maximum output	0.92	0.00	kW

Capacity factor	2.0	0.0	%

Quantity	Inverter	Rectifier	Units
Hours of operation	2,990	0	hrs/yr
Energy in	944	0	kWh/yr
Energy out	896	0	kWh/yr
Losses	47	0	kWh/yr



Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	289,325
Carbon monoxide	714
Unburned hydocarbons	79.1
Particulate matter	53.8
Sulfur dioxide	581
Nitrogen oxides	6,372

C1-9: System Report – Wind + PV + Diesel +Battery Storage

System architecture

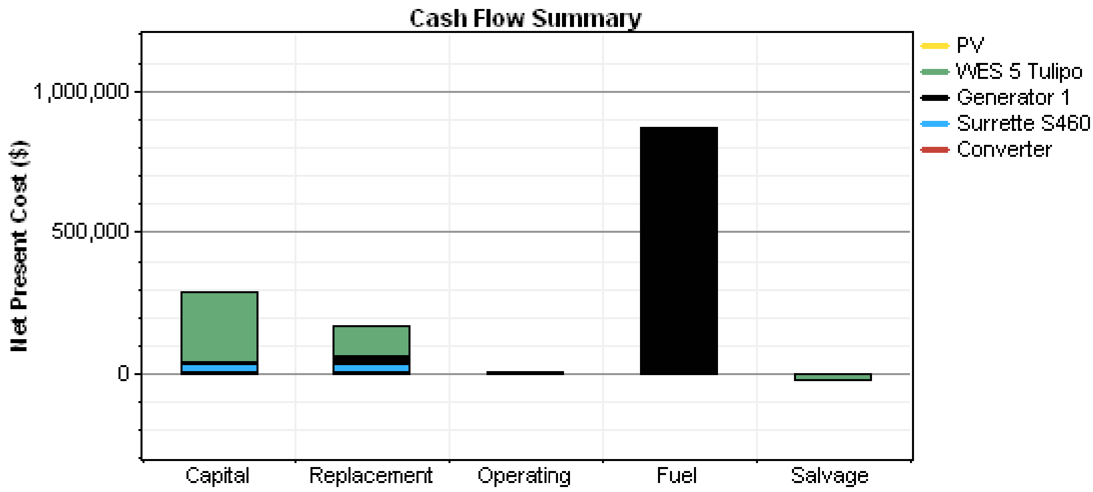
PV Array	0.2 kW
Wind turbine	20 WES 5 Tulipo
Generator 1	40 kW

Cost summary

Total net present cost	$ 1,305,209
Levelized cost of energy	$ 0.317/kWh

Battery	85 Surrette S460
Inverter	35 kW
Rectifier	35 kW
Dispatch strategy	Cycle Charging

Operating cost	$ 79,536/yr



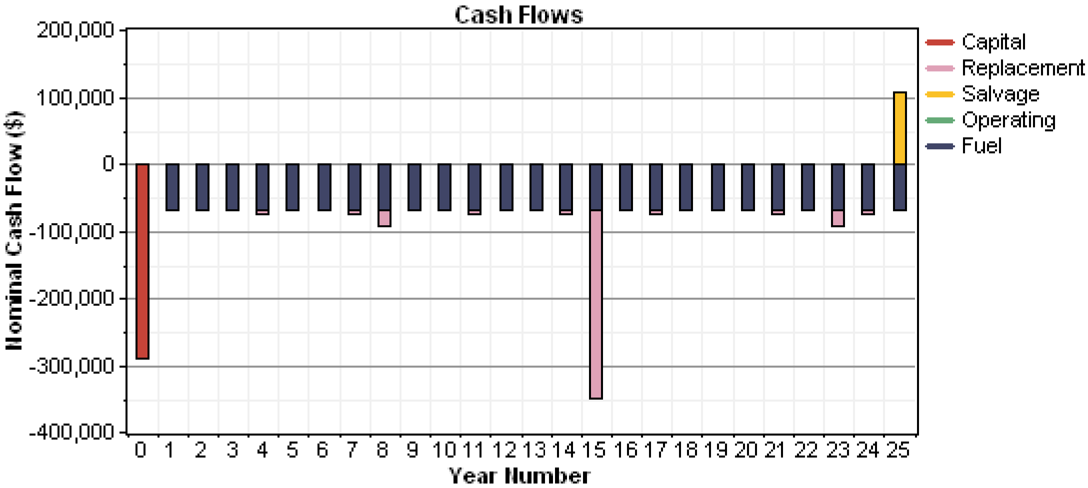
Net Present Costs

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	1,200	374	0	0	-210	1,364
WES 5 Tulipo	250,000	104,316	0	0	-19,417	334,900
Generator 1	7,701	26,446	3,777	870,680	-1,099	907,506
Surrette S460	25,500	34,249	0	0	-3,755	55,994
Converter	4,065	1,696	0	0	-316	5,445
System	288,467	167,082	3,777	870,680	-24,796	1,305,209

Annualized Costs

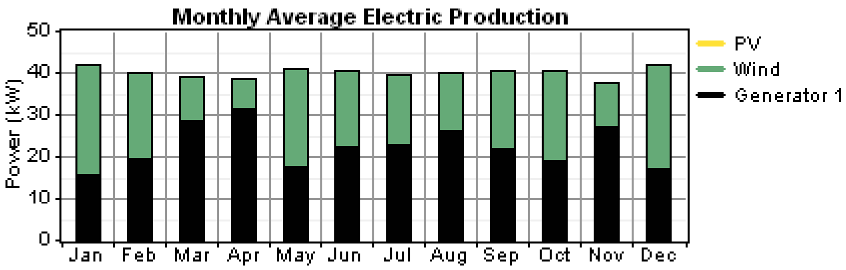
Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	94	29	0	0	-16	107
WES 5 Tulipo	19,557	8,160	0	0	-1,519	26,198
Generator 1	602	2,069	296	68,110	-86	70,991
Surrette S460	1,995	2,679	0	0	-294	4,380

Converter	318	133	0	0	-25	426
System	22,566	13,070	296	68,110	-1,940	102,102



Electrical

Component	Production	Fraction
	(kWh/yr)	
PV array	311	0%
Wind turbines	154,133	44%
Generator 1	196,798	56%
Total	351,242	100%



Load	Consumption	Fraction
	(kWh/yr)	
AC primary load	322,245	100%
Total	322,245	100%

Excess electricity	21,605	kWh/yr
Unmet load	50.8	kWh/yr
Capacity shortage	124	kWh/yr
Renewable fraction	0.440	

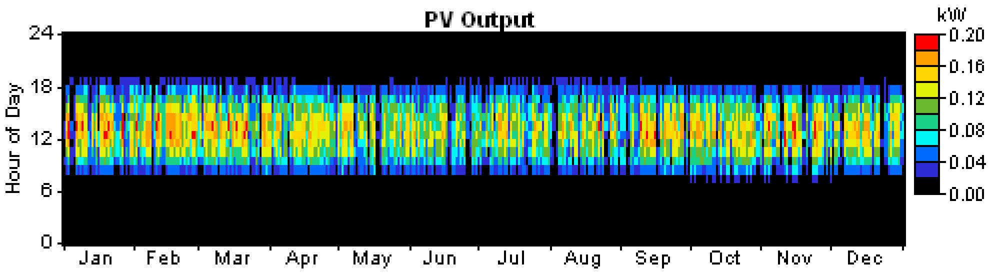
Quantity	Value	Units

PV

Quantity	Value	Units

Rated capacity	0.200	kW
Mean output	0.0355	kW
Mean output	0.852	kWh/d
Capacity factor	17.8	%
Total production	311	kWh/yr

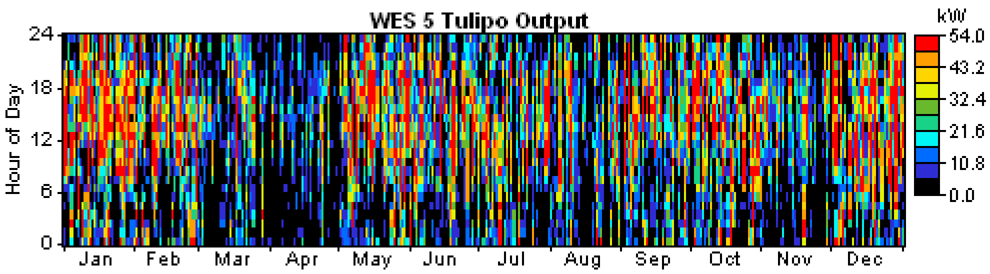
Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	0.194	kW
PV penetration	0.0965	%
Hours of operation	4,380	hr/yr
Levelized cost	0.343	$/kWh



AC Wind Turbine: WES 5 Tulipo

Variable	Value	Units
Total rated capacity	50.0	kW
Mean output	17.6	kW
Capacity factor	35.2	%
Total production	154,133	kWh/yr

Variable	Value	Units
Minimum output	0.00	kW
Maximum output	52.5	kW
Wind penetration	47.8	%
Hours of operation	7,904	hr/yr
Levelized cost	0.170	$/kWh



Generator 1

Quantity	Value	Units
Hours of operation	5,910	hr/yr
Number of starts	625	starts/yr

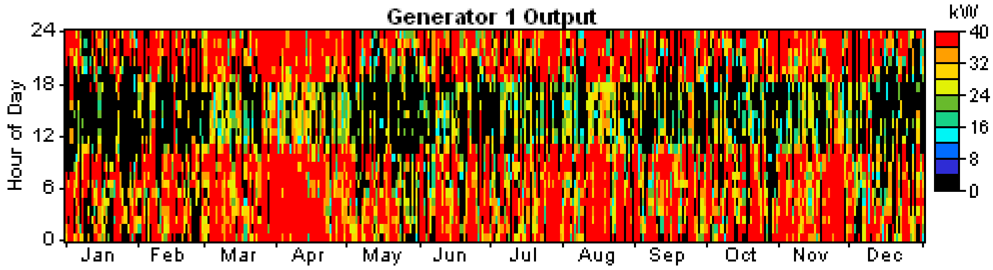
Operational life	3.38	yr
Capacity factor	56.2	%
Fixed generation cost	3.64	$/hr

Marginal generation cost	0.250	$/kWhyr

Quantity	Value	Units
Electrical production	196,798	kWh/yr

Quantity	Value	Units
Fuel consumption	68,110	L/yr
Specific fuel consumption	0.346	L/kWh
Fuel energy input	670,206	kWh/yr
Mean electrical efficiency	29.4	%

Mean electrical output	33.3	kW
Min. electrical output	12.0	kW
Max. electrical output	40.0	kW



Battery

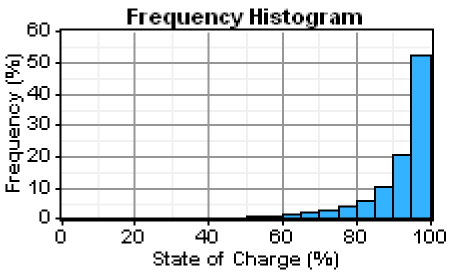
Quantity	Value
String size	1

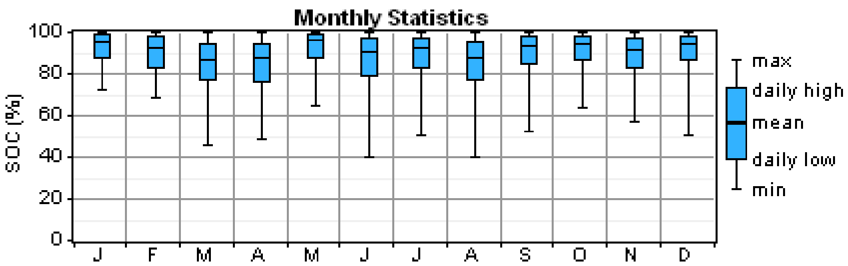
Strings in parallel	85
Batteries	85
Bus voltage (V)	6

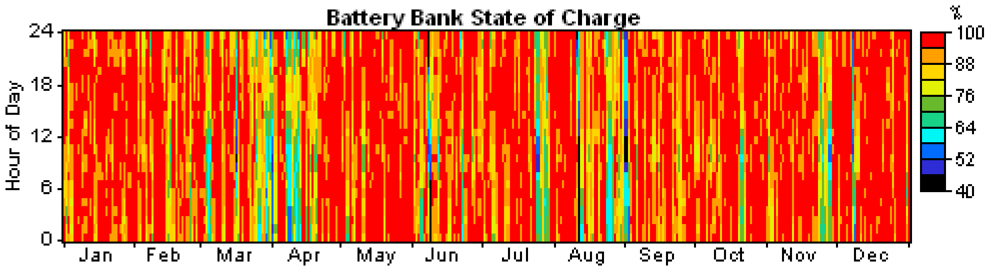
Quantity	Value	Units
Nominal capacity	235	kWh
Usable nominal capacity	141	kWh
Autonomy	3.83	hr
Lifetime throughput	118,490	kWh
Battery wear cost	0.241	$/kWh
Average energy cost	0.265	$/kWh

Expected life	7.42	yr

Quantity	Value	Units
Energy in	17,846	kWh/yr
Energy out	14,278	kWh/yr
Storage depletion	1.03	kWh/yr
Losses	3,567	kWh/yr
Annual throughput	15,963	kWh/yr

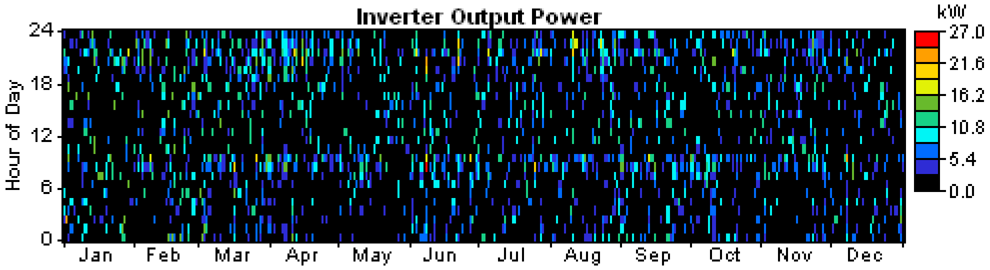


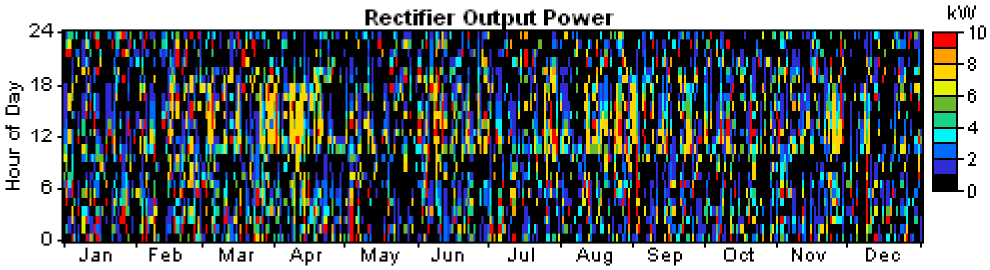




Converter

Quantity	Inverter	Rectifier	Units
Capacity	35.0	35.0	kW
Mean output	1.6	2.0	kW
Minimum output	0.0	0.0	kW
Maximum output	25.8	9.2	kW
Capacity factor	4.4	5.7	%
Hours of operation	2,352	6,350	hrs/yr
Energy in	14,340	20,706	kWh/yr
Energy out	13,623	17,600	kWh/yr
Losses	717	3,106	kWh/yr





Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	179,357
Carbon monoxide	443
Unburned hydocarbons	49
Particulate matter	33.4
Sulfur dioxide	360
Nitrogen oxides	3,950

C2: Systems for Severely Constrained Demand

Same sensitivities are considered for the systems with severe constraints as taken for the present demand but a deferrable peak load of 2 kW have been chosen for the simulations.

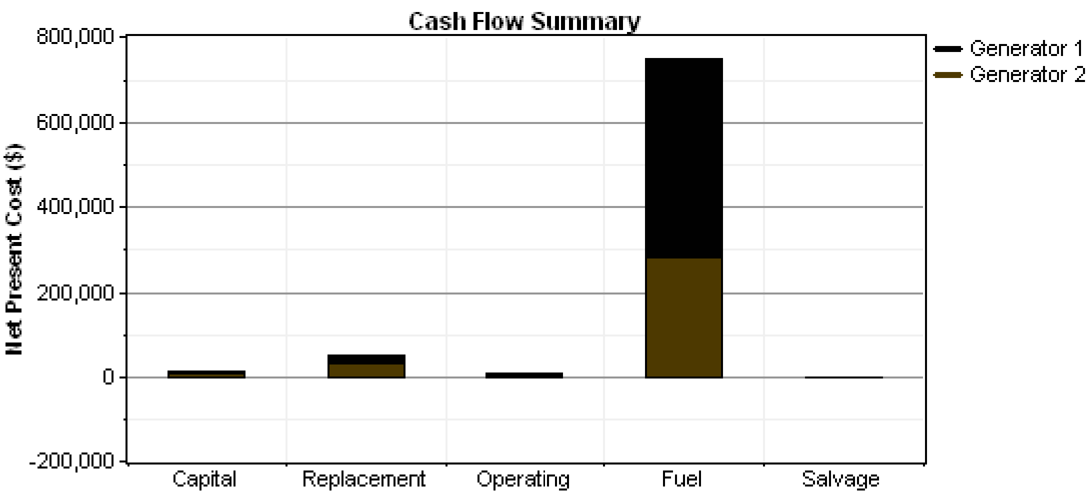
C2-1: System Report - Diesel only

System architecture

Generator 1	20 kW
Generator 2	12 kW

Cost summary

Total net present cost	$ 816,037
Levelized cost of energy	$ 0.465/kWh
Operating cost	$ 62,900/yr



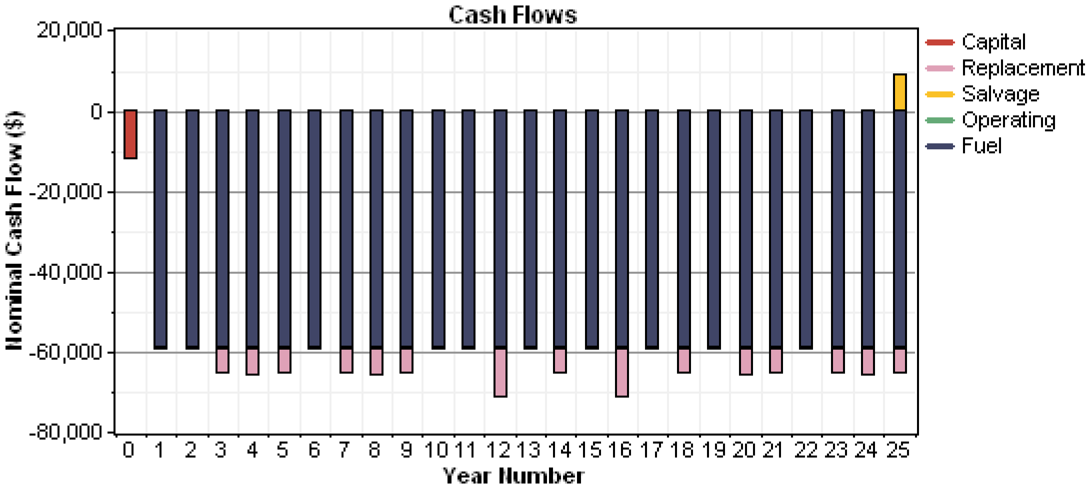
Net Present Costs

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generator 1	6,269	18,178	3,248	469,916	-946	496,665
Generator 2	5,696	31,109	4,275	279,423	-1,130	319,373
System	11,964	49,287	7,524	749,339	-2,076	816,038

Annualized Costs

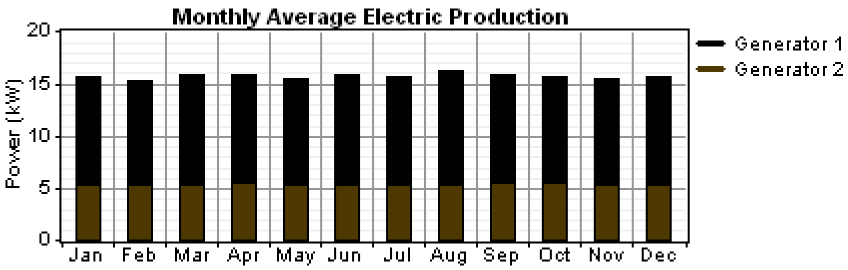
Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)

Generator 1	490	1,422	254	36,760	-74	38,852
Generator 2	446	2,434	334	21,858	-88	24,983
System	936	3,856	589	58,618	-162	63,836



Electrical

Component	Production	Fraction
	(kWh/yr)	
Generator 1	90,010	66%
Generator 2	47,175	34%
Total	137,186	100%



Load	Consumption	Fraction
	(kWh/yr)	
AC primary load	124,456	91%
Deferrable load	12,729	9%
Total	137,186	100%

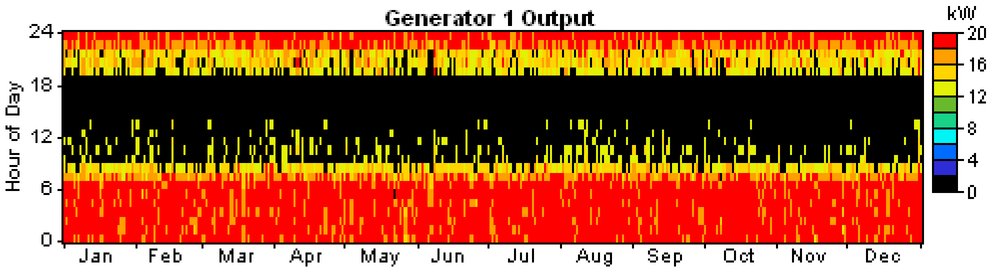
Quantity	Value	Units
Excess electricity	0.377	kWh/yr
Unmet load	8.57	kWh/yr
Capacity shortage	103	kWh/yr
Renewable fraction	0.000	

Generator 1

Quantity	Value	Units
Hours of operation	5,082	hr/yr
Number of starts	523	starts/yr
Operational life	3.94	yr
Capacity factor	51.4	%
Fixed generation cost	2.28	$/hr
Marginal generation cost	0.300	$/kWhyr

Quantity	Value	Units
Electrical production	90,010	kWh/yr
Mean electrical output	17.7	kW
Min. electrical output	12.4	kW
Max. electrical output	20.0	kW

Quantity	Value	Units
Fuel consumption	30,633	L/yr
Specific fuel consumption	0.340	L/kWh
Fuel energy input	301,432	kWh/yr
Mean electrical efficiency	29.9	%

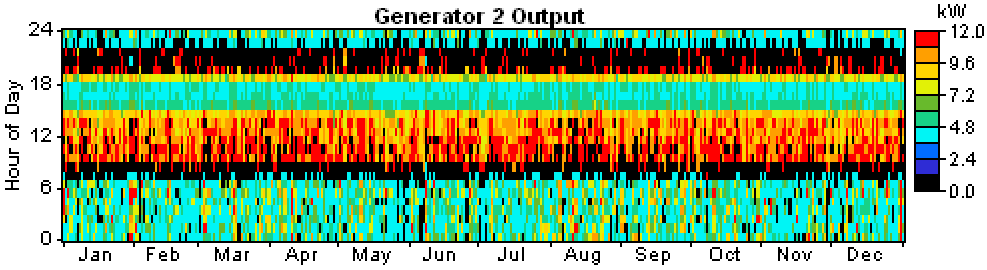


Generator 2

Quantity	Value	Units
Hours of operation	6,689	hr/yr
Number of starts	992	starts/yr
Operational life	2.24	yr
Capacity factor	44.9	%
Fixed generation cost	1.58	$/hr
Marginal generation cost	0.300	$/kWhyr

Quantity	Value	Units
Electrical production	47,175	kWh/yr
Mean electrical output	7.05	kW
Min. electrical output	3.60	kW
Max. electrical output	12.0	kW

Quantity	Value	Units
Fuel consumption	18,215	L/yr
Specific fuel consumption	0.386	L/kWh
Fuel energy input	179,238	kWh/yr
Mean electrical efficiency	26.3	%



Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	128,634
Carbon monoxide	318
Unburned hydocarbons	35.2
Particulate matter	23.9
Sulfur dioxide	258
Nitrogen oxides	2,833

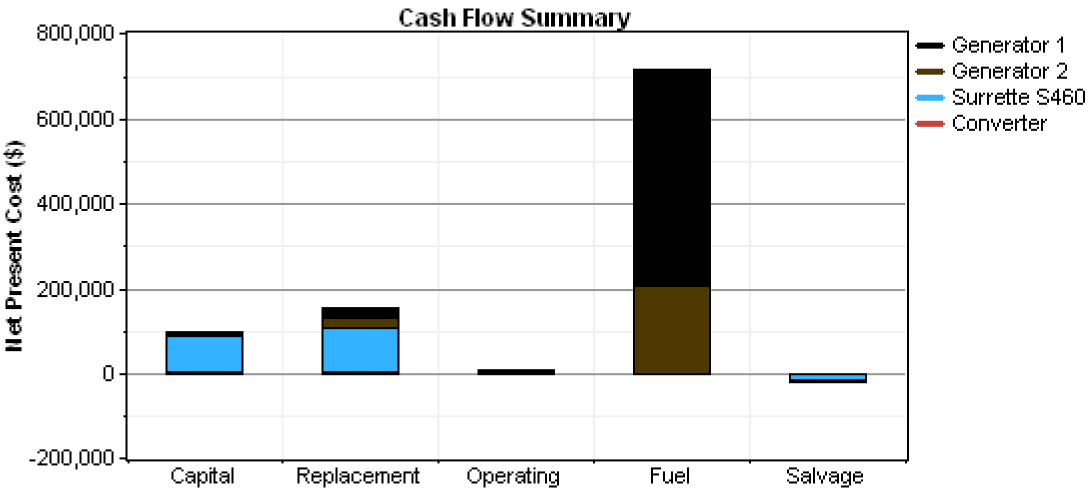
C2-2: System Report – Diesel + Battery Storage

System architecture

Generator 1	16 kW
Generator 2	8 kW
Battery	270 Surrette S460
Inverter	40 kW
Rectifier	40 kW
Dispatch strategy	Cycle Charging

Cost summary

Total net present cost	$ 953,179
Levelized cost of energy	$ 0.544/kWh
Operating cost	$ 66,973/yr

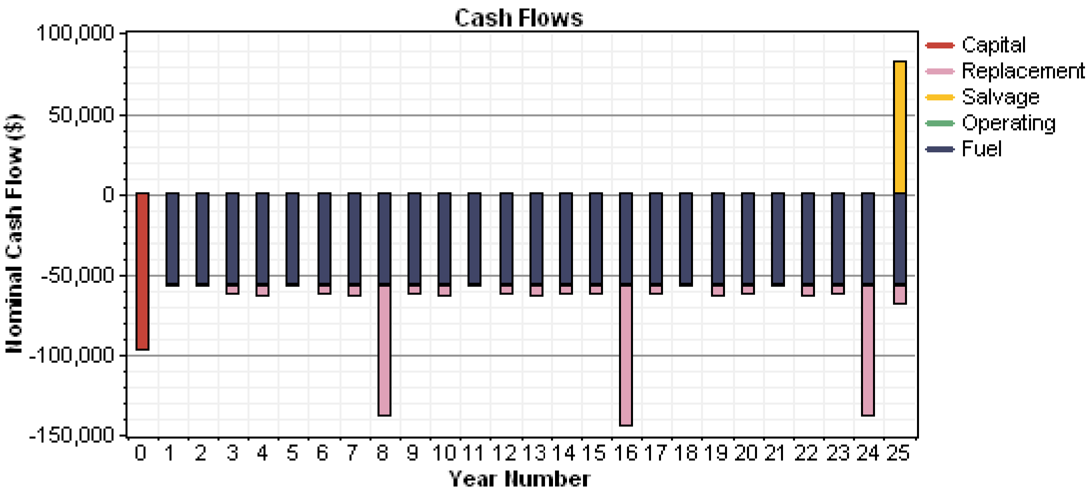


Net Present Costs

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generator 1	5,982	23,214	4,157	509,498	-1,213	541,639
Generator 2	5,409	23,677	3,466	206,776	-1,212	238,116
Surrette S460	81,000	102,711	0	0	-16,514	167,197
Converter	4,648	1,940	0	0	-361	6,227
System	97,039	151,542	7,623	716,274	-19,299	953,180

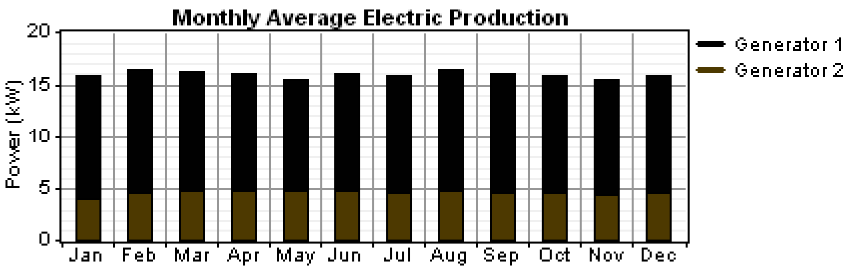
Annualized Costs

Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
Generator 1	468	1,816	325	39,856	-95	42,371
Generator 2	423	1,852	271	16,175	-95	18,627
Surrette S460	6,336	8,035	0	0	-1,292	13,079
Converter	364	152	0	0	-28	487
System	7,591	11,855	596	56,032	-1,510	74,564



Electrical

Component	Production	Fraction
	(kWh/yr)	
Generator 1	99,559	71%
Generator 2	40,037	29%
Total	139,596	100%



Load	Consumption	Fraction
	(kWh/yr)	
AC primary load	124,463	91%
Deferrable load	12,724	9%
Total	137,187	100%

Quantity	Value	Units
Excess electricity	0.000624	kWh/yr
Unmet load	3.50	kWh/yr
Capacity shortage	13.3	kWh/yr
Renewable fraction	0.000	

Generator 1

Quantity	Value	Units
Hours of operation	6,504	hr/yr
Number of starts	579	starts/yr
Operational life	3.08	yr

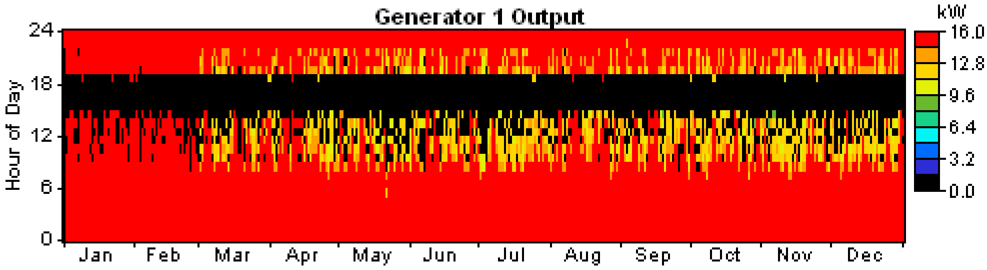
Capacity factor	71.0	%
Fixed generation cost	1.89	$/hr
Marginal generation cost	0.300	$/kWhyr

Quantity	Value	Units
Electrical production	99,559	kWh/yr

Mean electrical output	15.3	kW
Min. electrical output	9.23	kW

Max. electrical output	16.0	kW

Quantity	Value	Units
Fuel consumption	33,214	L/yr
Specific fuel consumption	0.334	L/kWh
Fuel energy input	326,822	kWh/yr
Mean electrical efficiency	30.5	%

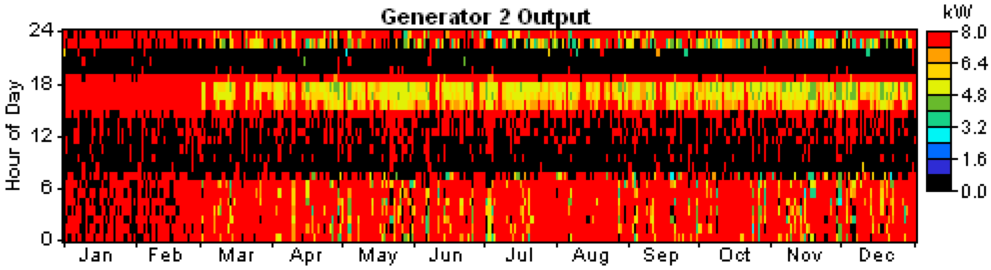


Generator 2

Quantity	Value	Units
Hours of operation	5,423	hr/yr
Number of starts	1,098	starts/yr
Operational life	2.77	yr
Capacity factor	57.1	%
Fixed generation cost	1.18	$/hr
Marginal generation cost	0.300	$/kWhyr

Quantity	Value	Units
Electrical production	40,037	kWh/yr
Mean electrical output	7.38	kW
Min. electrical output	2.40	kW
Max. electrical output	8.00	kW

Quantity	Value	Units
Fuel consumption	13,479	L/yr
Specific fuel consumption	0.337	L/kWh
Fuel energy input	132,638	kWh/yr
Mean electrical efficiency	30.2	%

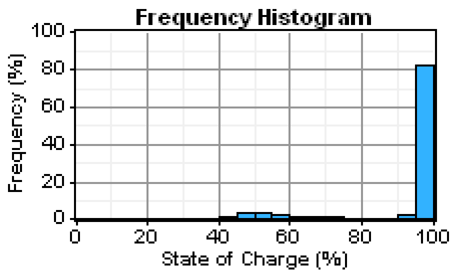


Battery

Quantity	Value
String size	1
Strings in parallel	270
Batteries	270
Bus voltage (V)	6

Quantity	Value	Units
Nominal capacity	745	kWh
Usable nominal capacity	447	kWh
Autonomy	28.5	hr
Lifetime throughput	376,380	kWh
Battery wear cost	0.241	$/kWh
Average energy cost	0.952	$/kWh

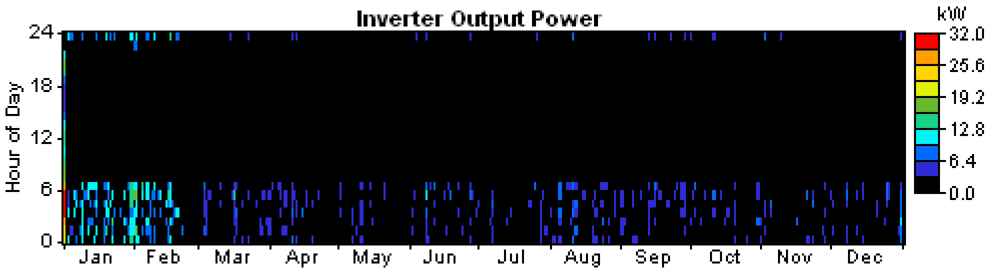
Quantity	Value	Units
Energy in	5,853	kWh/yr
Energy out	4,713	kWh/yr
Storage depletion	34.9	kWh/yr
Losses	1,105	kWh/yr
Annual throughput	5,269	kWh/yr
Expected life	8.00	yr

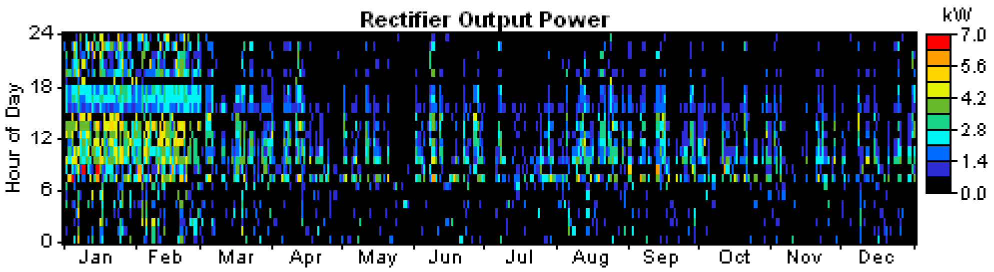


Converter

Quantity	Inverter	Rectifier	Units
Capacity	40.0	40.0	kW
Mean output	0.5	0.7	kW
Minimum output	0.0	0.0	kW
Maximum output	31.3	6.5	kW
Capacity factor	1.3	1.7	%

Quantity	Inverter	Rectifier	Units
Hours of operation	1,703	5,333	hrs/yr
Energy in	4,713	6,886	kWh/yr
Energy out	4,477	5,853	kWh/yr
Losses	236	1,033	kWh/yr





Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	122,958
Carbon monoxide	304
Unburned hydocarbons	33.6
Particulate matter	22.9
Sulfur dioxide	247
Nitrogen oxides	2,708

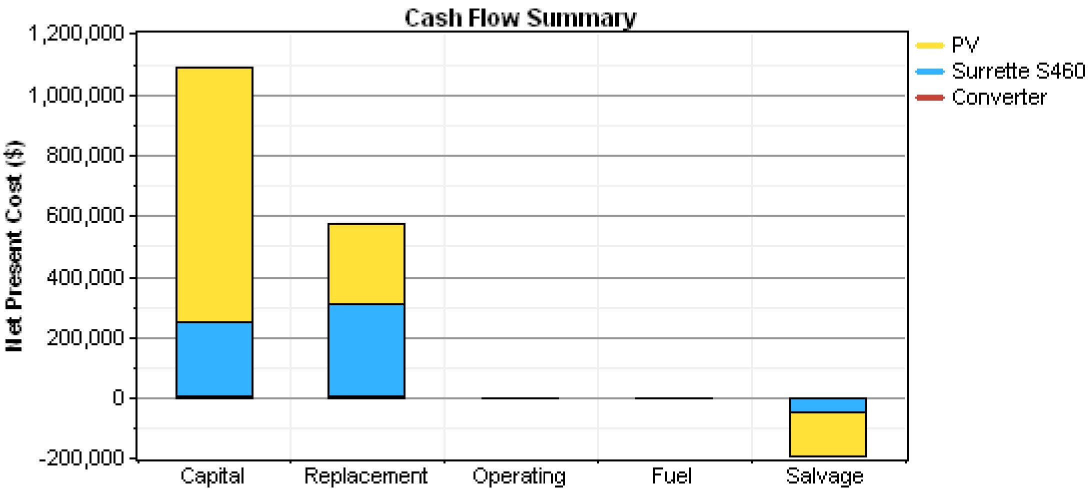
C2-3: System Report – PV+ Battery Storage

System architecture

PV Array	140 kW
Battery	810 Surrette S460
Inverter	40 kW
Rectifier	40 kW

Cost summary

Total net present cost	$ 1,462,945
Levelized cost of energy	$ 0.835/kWh
Operating cost	$ 29,358/yr

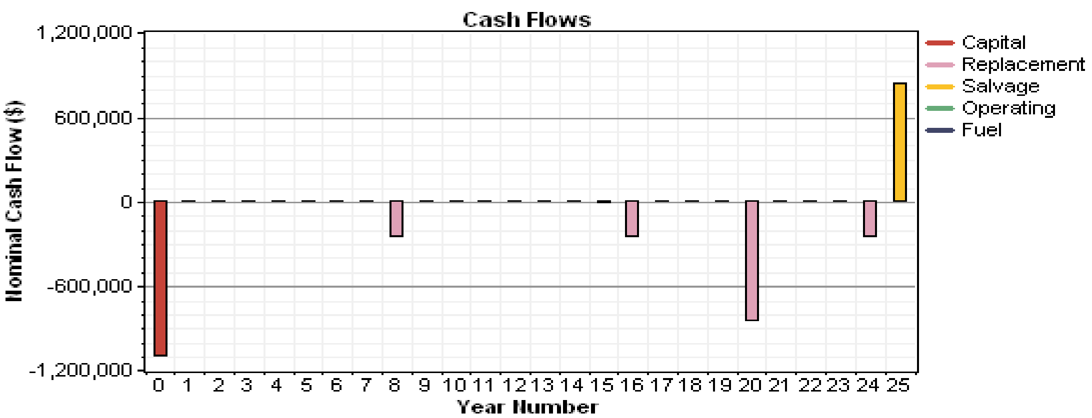


Net Present Costs

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	840,000	261,916	0	0	-146,789	955,127
Surrette S460	243,000	308,133	0	0	-49,541	501,592
Converter	4,648	1,940	0	0	-361	6,227
System	1,087,648	571,989	0	0	-196,692	1,462,946

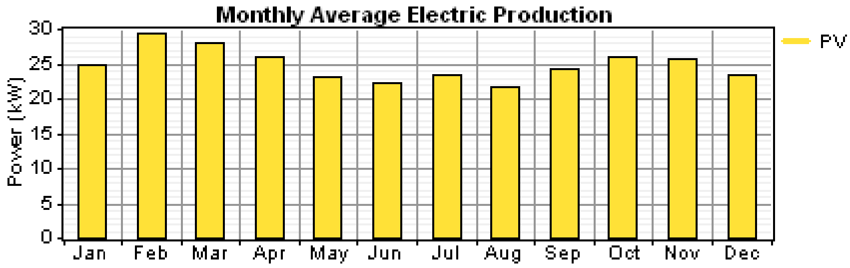
Annualized Costs

Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	65,710	20,489	0	0	-11,483	74,716
Surrette S460	19,009	24,104	0	0	-3,875	39,238
Converter	364	152	0	0	-28	487
System	85,083	44,745	0	0	-15,387	114,441



Electrical

Component	Production	Fraction
	(kWh/yr)	
PV array	217,707	100%
Total	217,707	100%



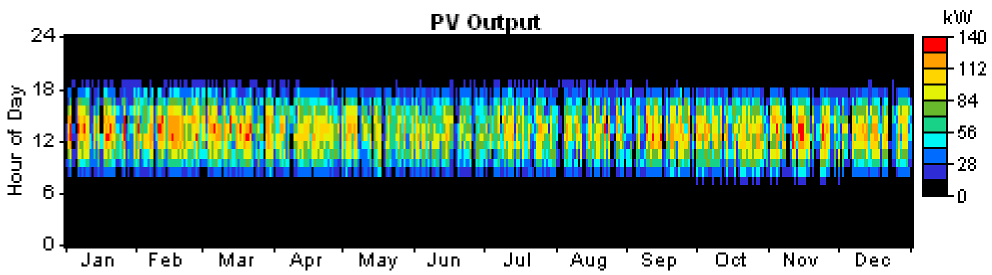
Load	Consumption	Fraction
	(kWh/yr)	
AC primary load	124,350	91%
Deferrable load	12,715	9%
Total	137,065	100%

Quantity	Value	Units
Excess electricity	48,511	kWh/yr
Unmet load	120	kWh/yr
Capacity shortage	135	kWh/yr
Renewable fraction	1.000	

PV

Quantity	Value	Units
Rated capacity	140	kW
Mean output	24.9	kW
Mean output	596	kWh/d
Capacity factor	17.8	%
Total production	217,707	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	136	kW
PV penetration	175	%
Hours of operation	4,380	hr/yr
Levelized cost	0.343	$/kWh



Battery

Quantity	Value

String size	1
Strings in parallel	810

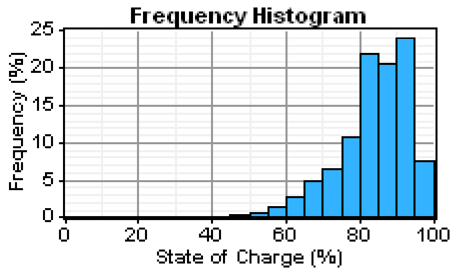
Batteries	810
Bus voltage (V)	6

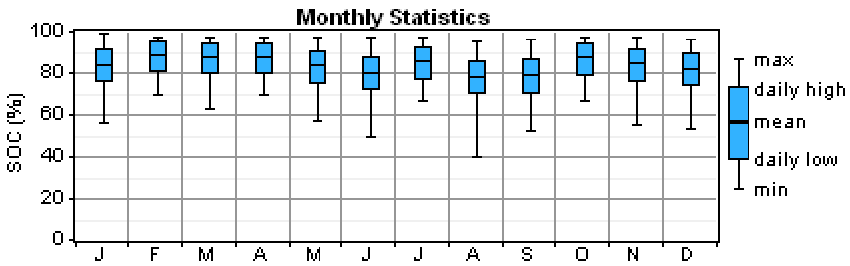
Quantity	Value	Units
Nominal capacity	2,236	kWh
Usable nominal capacity	1,341	kWh

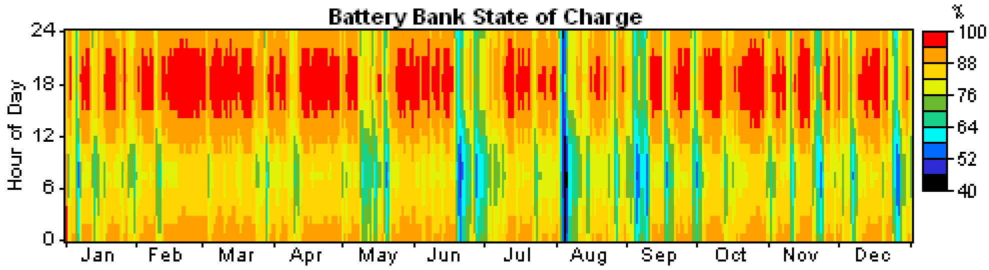
Autonomy	85.6	hr
Lifetime throughput	1,129,140	kWh
Battery wear cost	0.241	$/kWh
Average energy cost	0.000	$/kWh

Quantity	Value	Units
Energy in	126,828	kWh/yr
Energy out	101,910	kWh/yr
Storage depletion	513	kWh/yr
Losses	24,405	kWh/yr
Annual throughput	113,939	kWh/yr

Expected life	8.00	yr





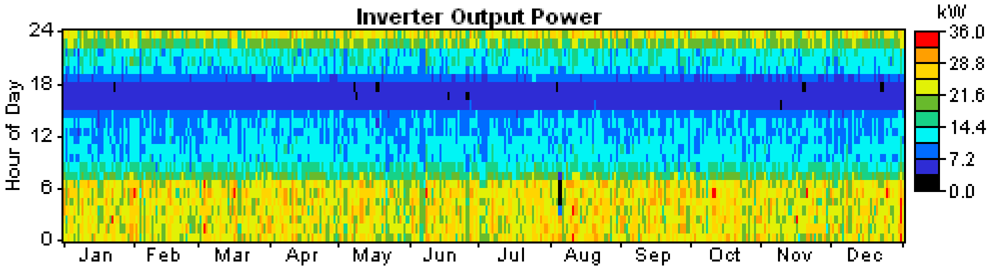


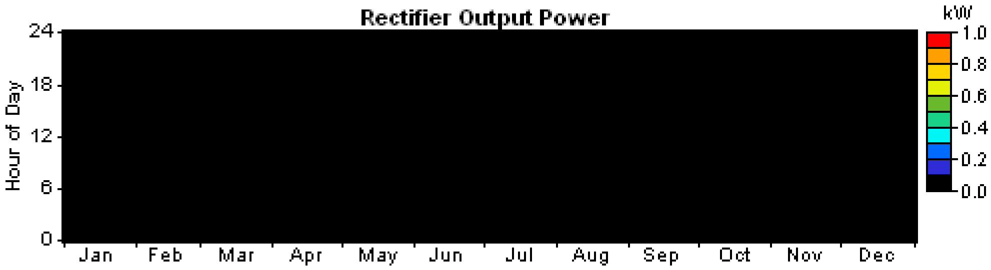
Converter

Quantity	Inverter	Rectifier	Units
Capacity	40.0	40.0	kW
Mean output	15.6	0.0	kW
Minimum output	0.0	0.0	kW
Maximum output	36.0	0.0	kW

Capacity factor	39.1	0.0	%

Quantity	Inverter	Rectifier	Units
Hours of operation	8,757	0	hrs/yr
Energy in	144,279	0	kWh/yr
Energy out	137,065	0	kWh/yr
Losses	7,214	0	kWh/yr





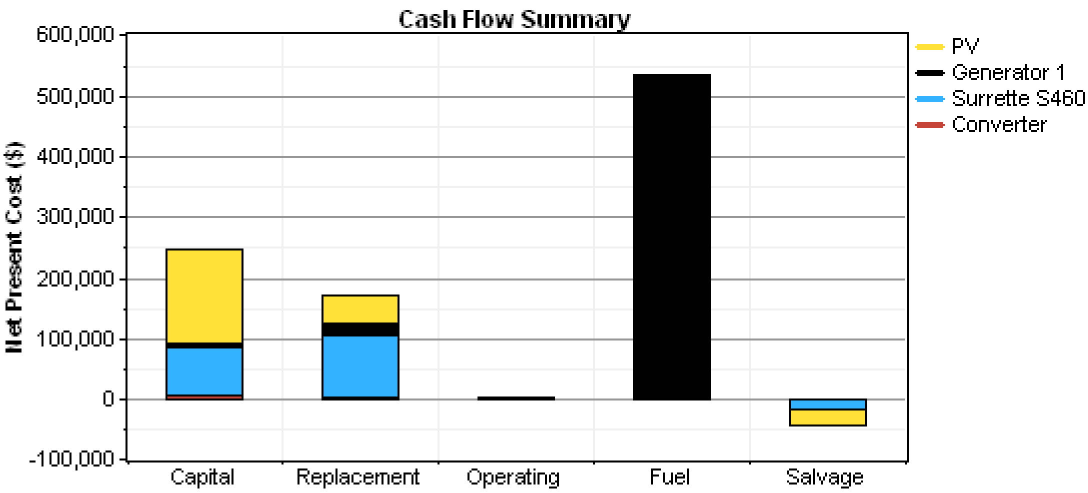
C2-4: System Report - PV+ Diesel +Battery Storage

System architecture

PV Array	26 kW
Generator 1	20 kW
Battery	270 Surrette S460
Inverter	40 kW
Rectifier	40 kW
Dispatch strategy	Cycle Charging

Cost summary

Total net present cost	$ 913,865
Levelized cost of energy	$ 0.521/kWh
Operating cost	$ 52,095/yr



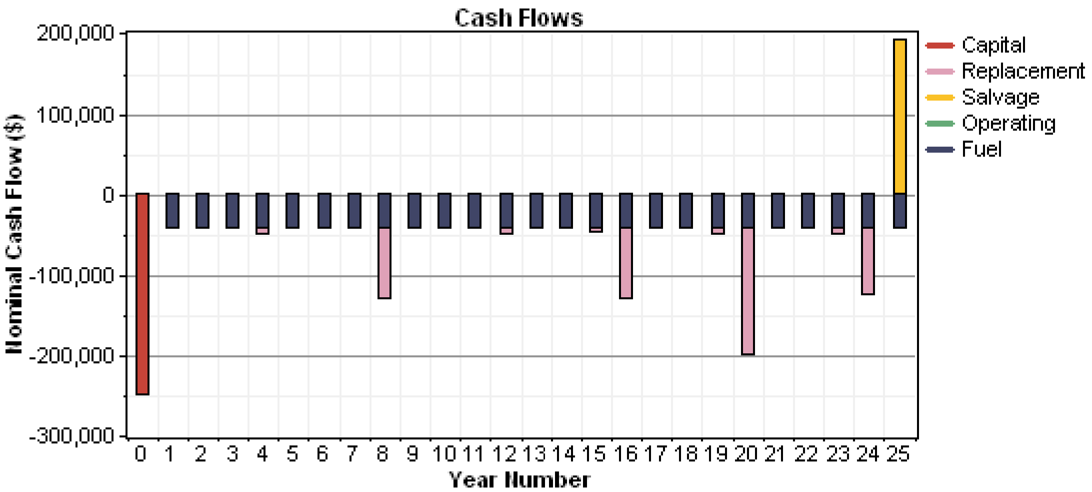
Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)

PV	156,000	48,642	0	0	-27,261	177,381
Generator 1	6,269	18,651	3,381	535,328	-568	563,060
Surrette S460	81,000	102,711	0	0	-16,514	167,197
Converter	4,648	1,940	0	0	-361	6,227
System	247,917	171,943	3,381	535,328	-44,704	913,866

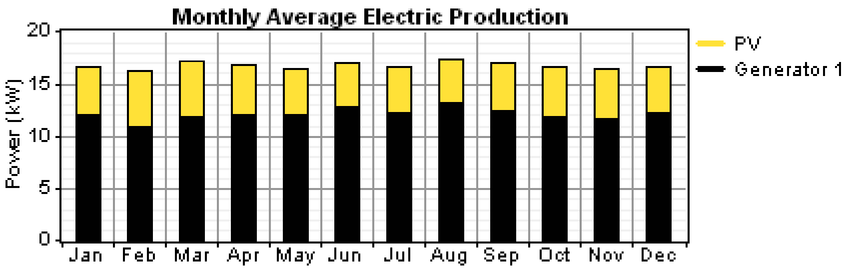
Annualized Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
PV	12,203	3,805	0	0	-2,133	13,876
Generator 1	490	1,459	264	41,877	-44	44,046
Surrette S460	6,336	8,035	0	0	-1,292	13,079
Converter	364	152	0	0	-28	487
System	19,394	13,451	264	41,877	-3,497	71,489



Electrical

Component	Production	Fraction
	(kWh/yr)	
PV array	40,431	28%
Generator 1	105,744	72%
Total	146,175	100%



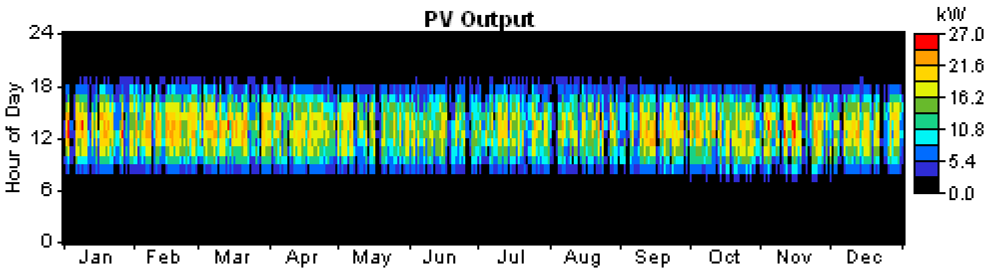
Load	Consumption (kWh/yr)	Fraction
AC primary load	124,454	91%
Deferrable load	12,692	9%
Total	137,146	100%

Quantity	Value	Units
Excess electricity	52.3	kWh/yr
Unmet load	38.8	kWh/yr
Capacity shortage	50.6	kWh/yr
Renewable fraction	0.277	

PV

Quantity	Value	Units
Rated capacity	26.0	kW
Mean output	4.62	kW
Mean output	111	kWh/d
Capacity factor	17.8	%
Total production	40,431	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	25.2	kW
PV penetration	32.5	%
Hours of operation	4,380	hr/yr
Levelized cost	0.343	$/kWh



Generator 1

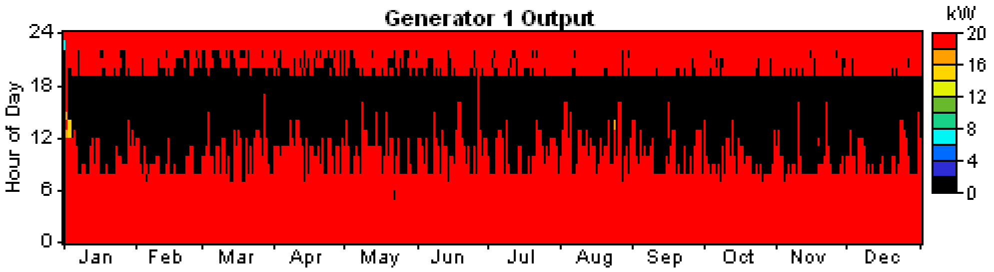
Quantity	Value	Units
Hours of operation	5,289	hr/yr
Number of starts	406	starts/yr
Operational life	3.78	yr
Capacity factor	60.4	%
Fixed generation cost	2.28	$/hr
Marginal generation cost	0.300	$/kWhyr

Quantity	Value	Units
Electrical production	105,744	kWh/yr
Mean electrical output	20.0	kW

Min. electrical output	7.67	kW

Quantity	Value	Units
Fuel consumption	34,897	L/yr
Specific fuel consumption	0.330	L/kWh
Fuel energy input	343,391	kWh/yr
Mean electrical efficiency	30.8	%

Max. electrical output	20.0	kW



Battery

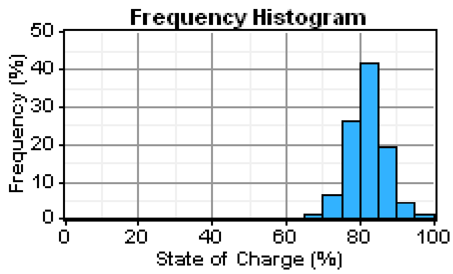
Quantity	Value
String size	1
Strings in parallel	270
Batteries	270
Bus voltage (V)	6

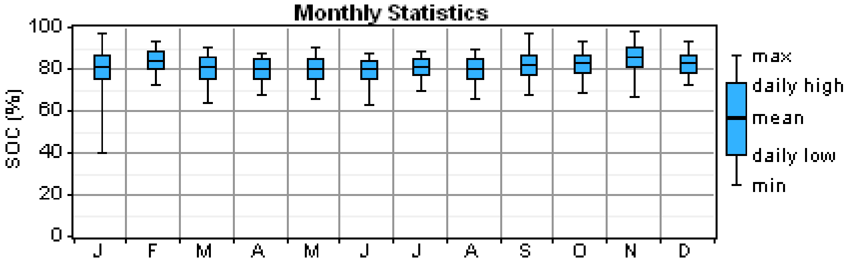
Quantity	Value	Units
Nominal capacity	745	kWh
Usable nominal capacity	447	kWh
Autonomy	28.5	hr
Lifetime throughput	376,380	kWh
Battery wear cost	0.241	$/kWh
Average energy cost	0.237	$/kWh

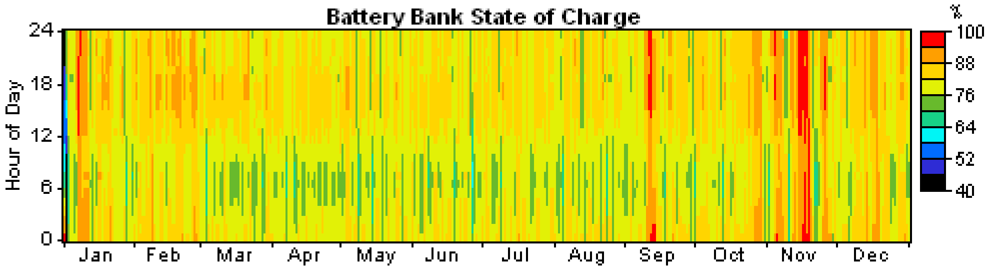
Quantity	Value	Units

Quantity	Value	Units
Energy in	26,265	kWh/yr
Energy out	21,148	kWh/yr
Storage depletion	155	kWh/yr
Losses	4,962	kWh/yr
Annual throughput	23,644	kWh/yr

Expected life	8.00	yr

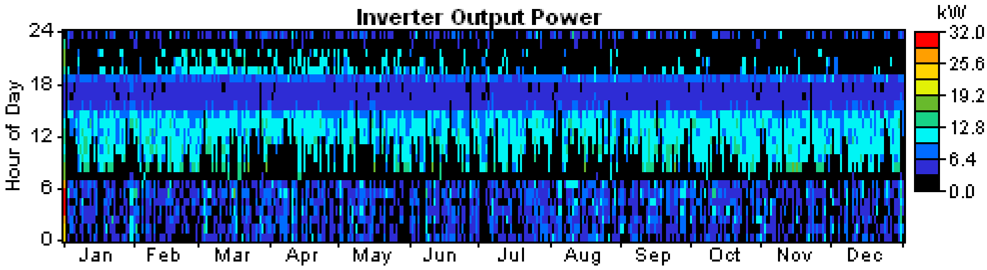


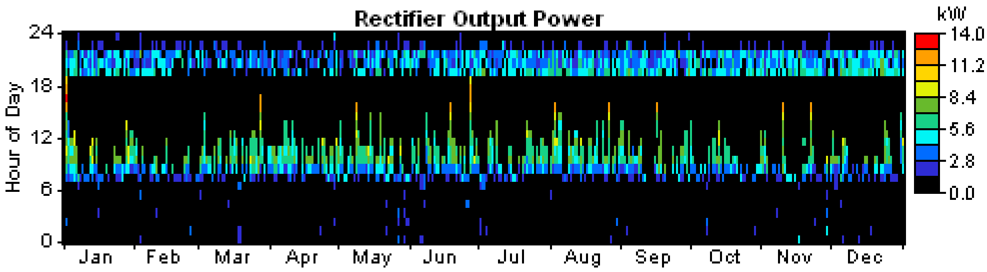




Converter

Quantity	Inverter	Rectifier	Units
Capacity	40.0	40.0	kW
Mean output	4.8	1.1	kW
Minimum output	0.0	0.0	kW
Maximum output	31.3	12.7	kW
Capacity factor	12.1	2.6	%
Hours of operation	6,157	2,224	hrs/yr
Energy in	44,517	10,889	kWh/yr
Energy out	42,291	9,255	kWh/yr
Losses	2,226	1,633	kWh/yr





Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	91,896

Carbon monoxide	227
Unburned hydocarbons	25.1
Particulate matter	17.1
Sulfur dioxide	185
Nitrogen oxides	2,024

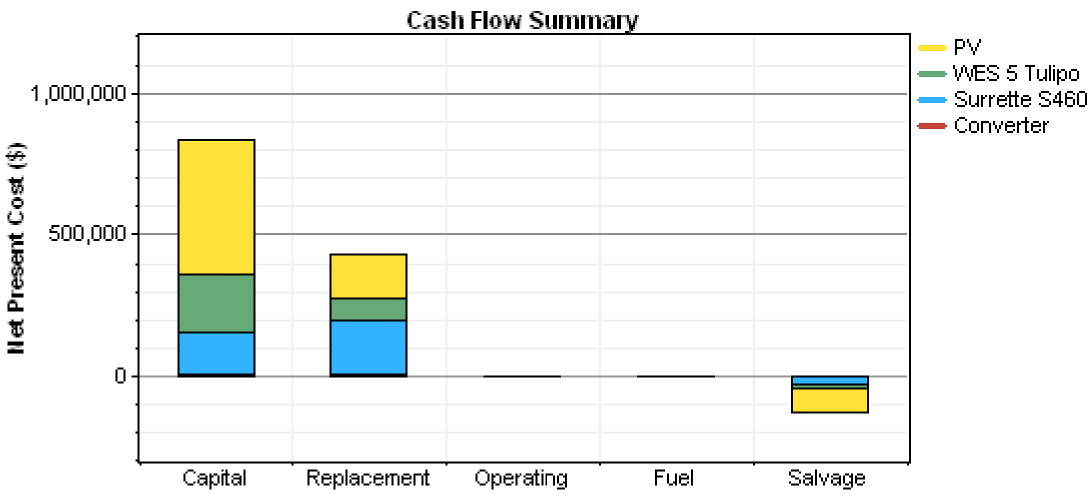
C2-5: System Report – Wind + PV + Battery Storage

System architecture

PV Array	80 kW
Wind turbine	16 WES 5 Tulipo
Battery	500 Surrette S460
Inverter	40 kW
Rectifier	40 kW

Cost summary

Total net present cost	$ 1,129,558
Levelized cost of energy	$ 0.645/kWh
Operating cost	$ 23,070/yr

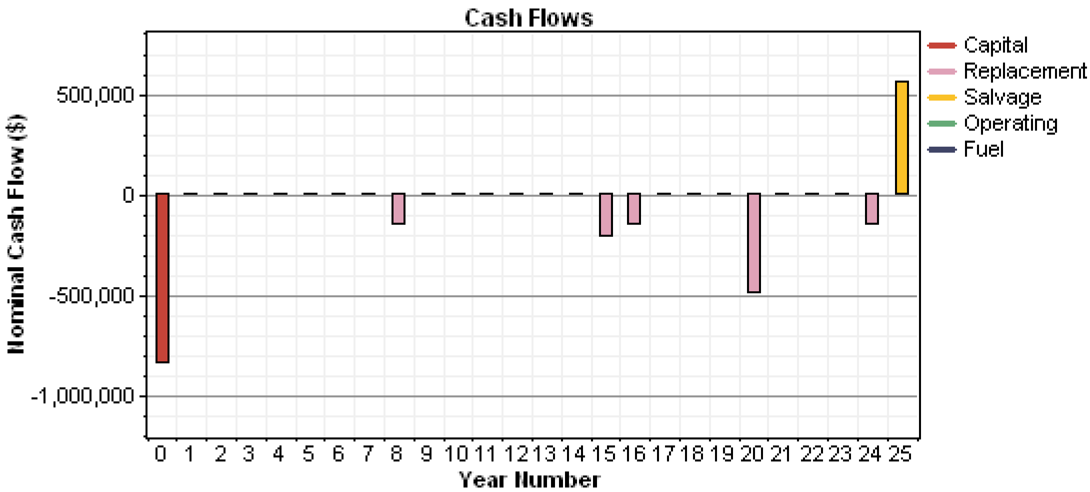


Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)
PV	480,000	149,666	0	0	-83,880	545,787
WES 5 Tulipo	200,000	83,453	0	0	-15,533	267,920
Surrette S460	150,000	190,206	0	0	-30,581	309,625
Converter	4,648	1,940	0	0	-361	6,227
System	834,648	425,265	0	0	-130,355	1,129,558

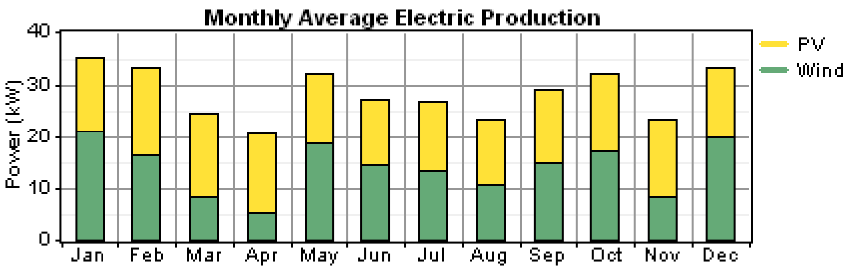
Annualized Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
PV	37,549	11,708	0	0	-6,562	42,695
WES 5 Tulipo	15,645	6,528	0	0	-1,215	20,958
Surrette S460	11,734	14,879	0	0	-2,392	24,221
Converter	364	152	0	0	-28	487
System	65,292	33,267	0	0	-10,197	88,362



Electrical

Component	Production	Fraction
	(kWh/yr)	
PV array	124,404	50%
Wind turbines	123,306	50%
Total	247,710	100%



Load	Consumption	Fraction
	(kWh/yr)	
AC primary load	124,367	91%
Deferrable load	12,712	9%

Total	137,080	100%

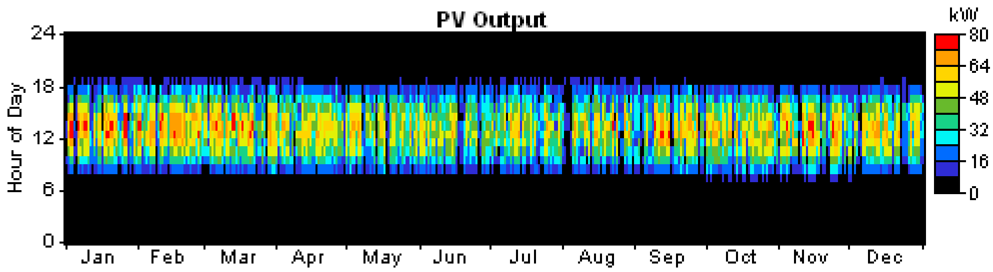
Quantity	Value	Units
Excess electricity	88,665	kWh/yr

Unmet load	106	kWh/yr
Capacity shortage	133	kWh/yr
Renewable fraction	1.000	

PV

Quantity	Value	Units
Rated capacity	80.0	kW
Mean output	14.2	kW
Mean output	341	kWh/d
Capacity factor	17.8	%
Total production	124,404	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	77.6	kW
PV penetration	100.0	%
Hours of operation	4,380	hr/yr
Levelized cost	0.343	$/kWh

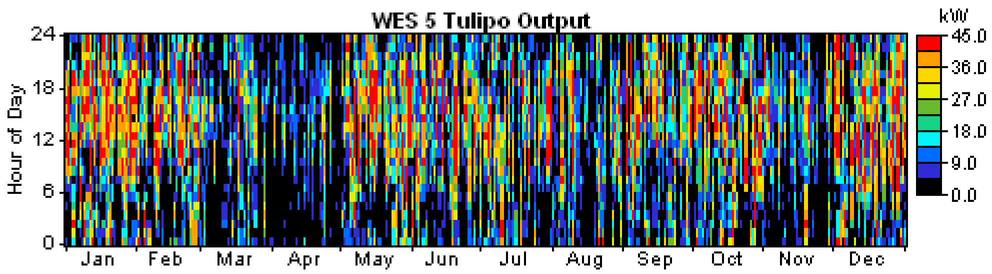


AC Wind Turbine: WES 5 Tulipo

Variable	Value	Units
Total rated capacity	40.0	kW
Mean output	14.1	kW
Capacity factor	35.2	%
Total production	123,306	kWh/yr

Minimum output	0.00	kW
Maximum output	42.0	kW
Wind penetration	99.1	%
Hours of operation	7,904	hr/yr
Levelized cost	0.170	$/kWh

Variable	Value	Units



Battery

Quantity	Value

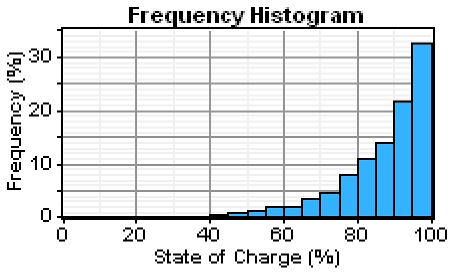
Quantity	Value	Units
Nominal capacity	1,380	kWh
Usable nominal capacity	828	kWh

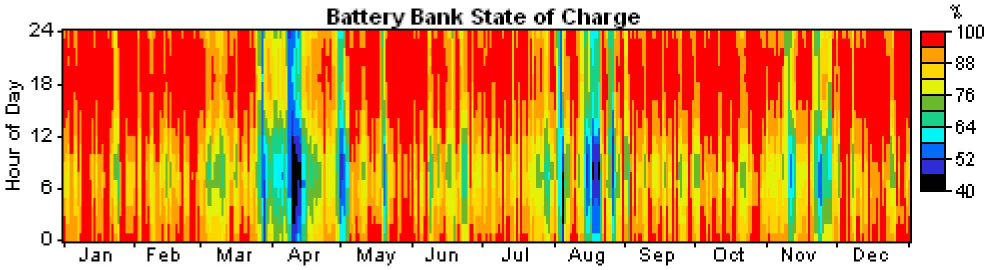
String size	1
Strings in parallel	500
Batteries	500
Bus voltage (V)	6

Autonomy	52.9	hr
Lifetime throughput	697,000	kWh
Battery wear cost	0.241	$/kWh
Average energy cost	0.000	$/kWh

Quantity	Value	Units
Energy in	79,260	kWh/yr
Energy out	63,450	kWh/yr
Storage depletion	47.7	kWh/yr
Losses	15,763	kWh/yr
Annual throughput	70,939	kWh/yr

Expected life	8.00	yr



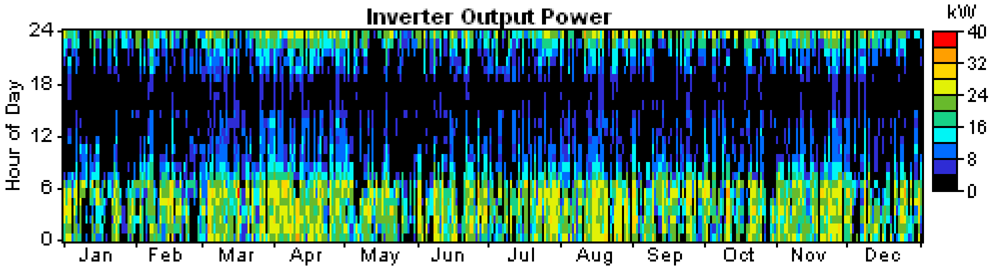


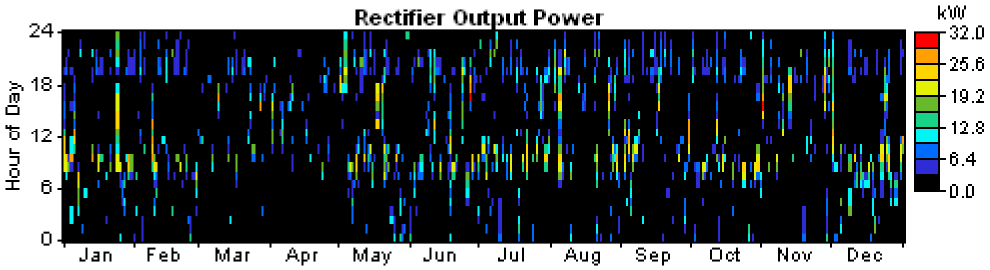
Converter

Quantity	Inverter	Rectifier	Units
Capacity	40.0	40.0	kW
Mean output	8.2	1.5	kW
Minimum output	0.0	0.0	kW
Maximum output	37.4	30.3	kW
Capacity	20.5	3.8	%

factor			

Quantity	Inverter	Rectifier	Units
Hours of operation	5,293	1,889	hrs/yr
Energy in	75,724	15,791	kWh/yr
Energy out	71,937	13,423	kWh/yr
Losses	3,786	2,369	kWh/yr





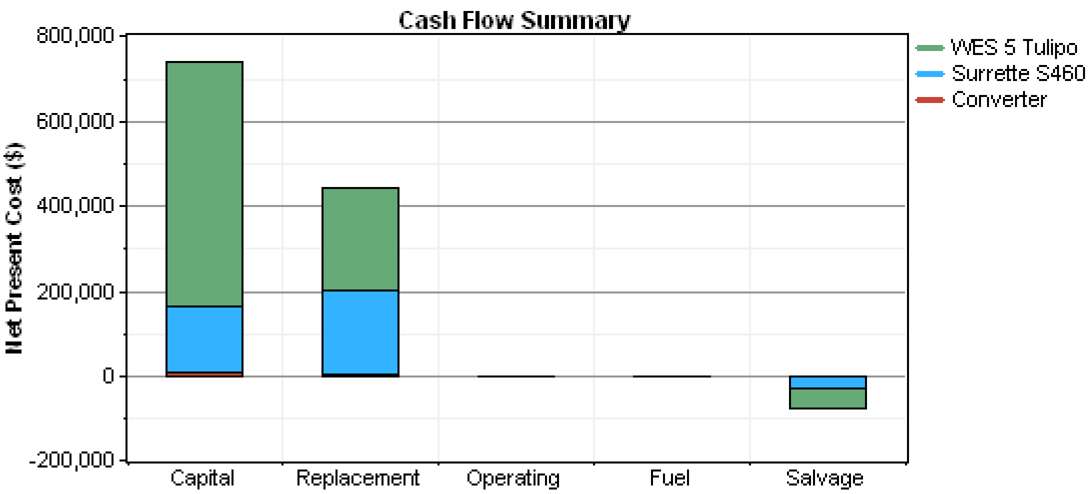
C2-6: System Report – Wind + Battery Storage

System architecture

Wind turbine	46 WES 5 Tulipo
Battery	520 Surrette S460
Inverter	55 kW
Rectifier	55 kW

Cost summary

Total net present cost	$ 1,100,850
Levelized cost of energy	$ 0.653/kWh
Operating cost	$ 28,432/yr



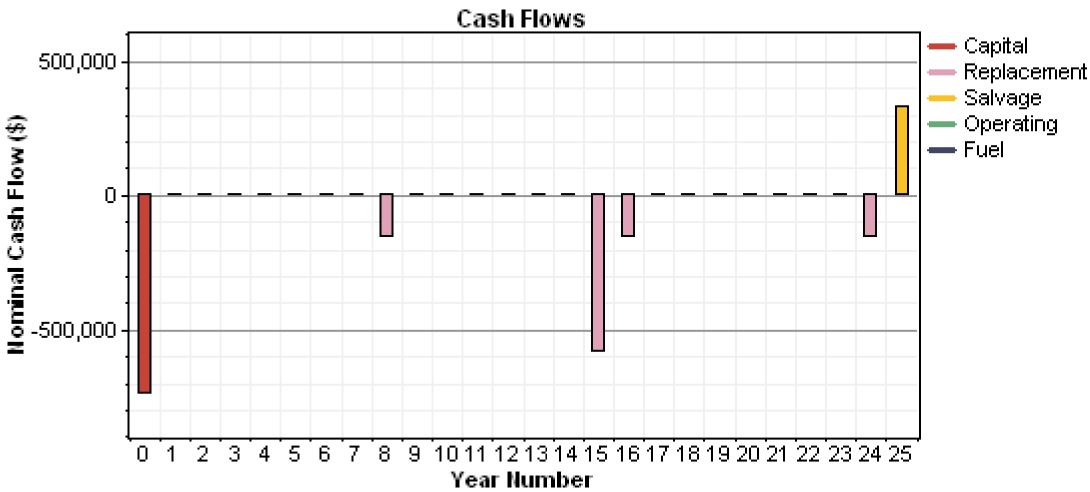
Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)
WES 5 Tulipo	575,000	239,928	0	0	-44,658	770,270

Surrette S460	156,000	197,814	0	0	-31,804	322,010
Converter	6,398	2,670	0	0	-497	8,571
System	737,398	440,411	0	0	-76,959	1,100,850

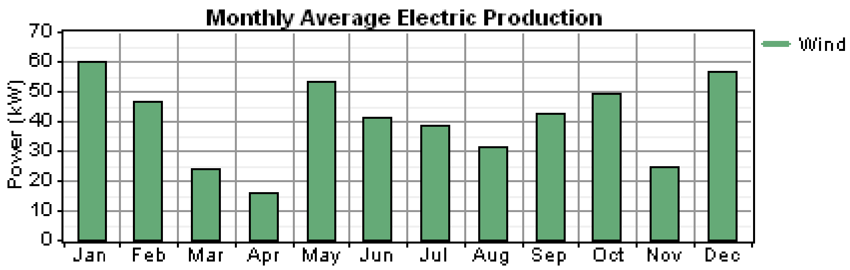
Annualized Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
WES 5 Tulipo	44,980	18,769	0	0	-3,493	60,256
Surrette S460	12,203	15,474	0	0	-2,488	25,190
Converter	501	209	0	0	-39	670
System	57,684	34,452	0	0	-6,020	86,116



Electrical

Component	Production	Fraction
	(kWh/yr)	
Wind turbines	354,505	100%
Total	354,505	100%



Load	Consumption	Fraction
	(kWh/yr)	

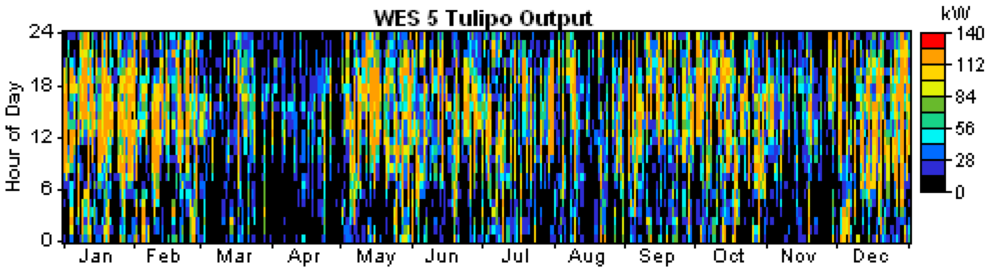
AC primary load	119,607	91%
Deferrable load	12,200	9%
Total	131,807	100%
Quantity	**Value**	**Units**

Excess electricity	198,975	kWh/yr
Unmet load	5,386	kWh/yr
Capacity shortage	6,923	kWh/yr
Renewable fraction	1.000	

AC Wind Turbine: WES 5 Tulipo

Variable	Value	Units
Total rated capacity	115	kW
Mean output	40.5	kW
Capacity factor	35.2	%
Total production	354,505	kWh/yr

Variable	Value	Units
Minimum output	0.00	kW
Maximum output	121	kW
Wind penetration	285	%
Hours of operation	7,904	hr/yr
Levelized cost	0.170	$/kWh



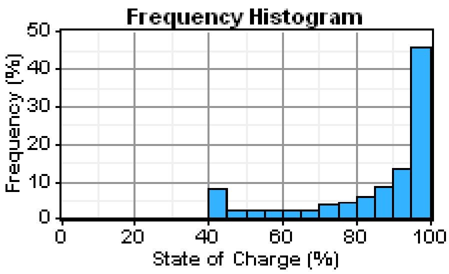
Battery

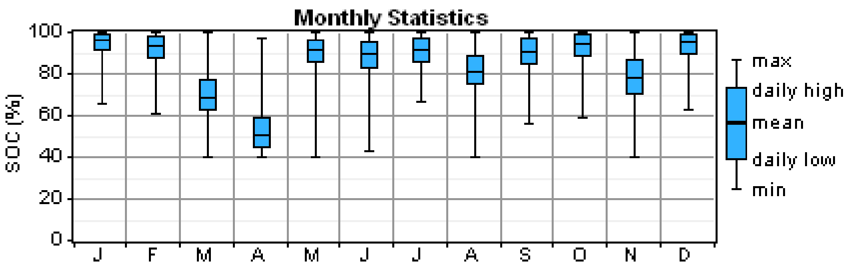
Quantity	Value
String size	1
Strings in parallel	520
Batteries	520
Bus voltage (V)	6

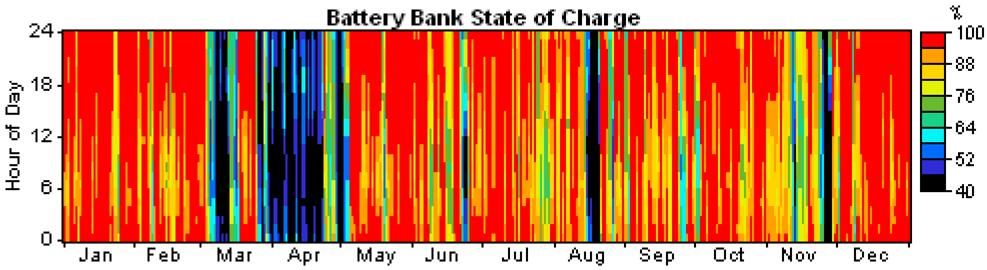
Quantity	**Value**	**Units**
Nominal capacity	1,435	kWh
Usable nominal capacity	861	kWh
Autonomy	55.0	hr
Lifetime throughput	724,880	kWh
Battery wear cost	0.241	$/kWh
Average energy cost	0.000	$/kWh

Quantity	Value	Units
Energy in	56,970	kWh/yr
Energy out	45,581	kWh/yr
Storage depletion	5.45	kWh/yr
Losses	11,384	kWh/yr

Annual throughput	50,961	kWh/yr
Expected life	8.00	yr



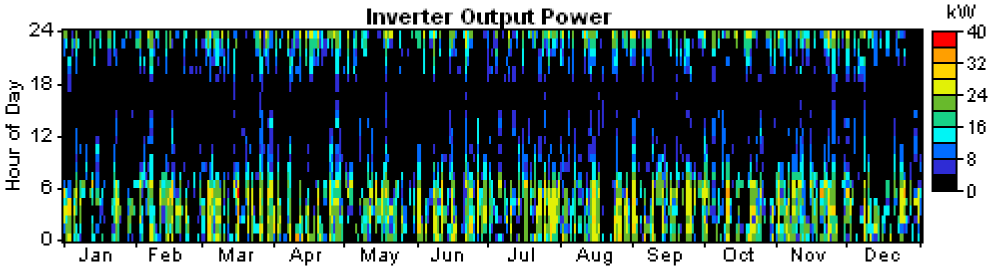


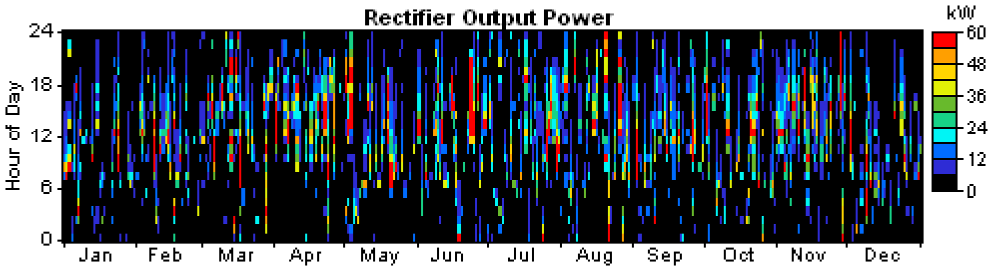


Converter

Quantity	Inverter	Rectifier	Units
Capacity	55.0	55.0	kW
Mean output	4.9	6.5	kW
Minimum output	0.0	0.0	kW
Maximum output	36.4	55.0	kW
Capacity factor	9.0	11.8	%

Quantity	Inverter	Rectifier	Units
Hours of operation	3,140	5,122	hrs/yr
Energy in	45,581	67,024	kWh/yr
Energy out	43,302	56,970	kWh/yr
Losses	2,279	10,054	kWh/yr





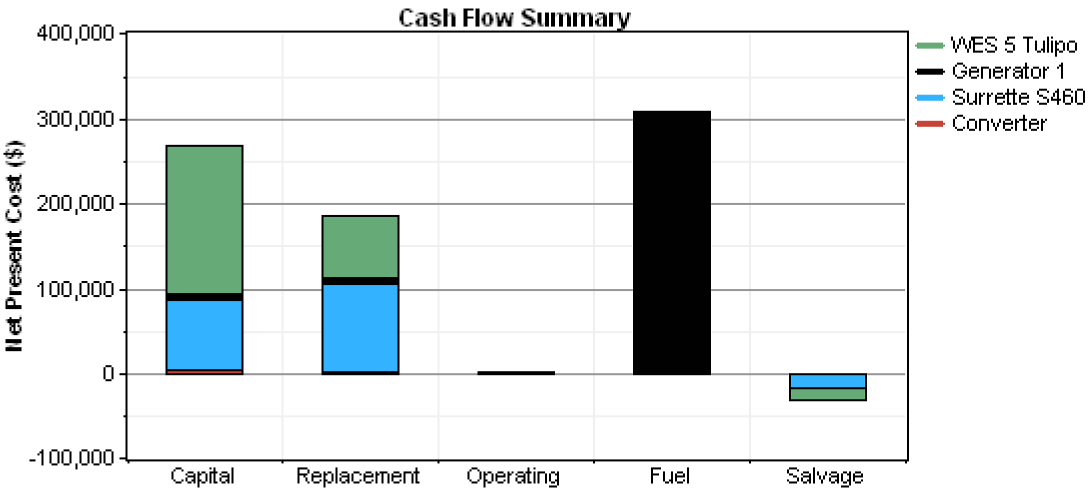
C2-7: System Report – Wind + Diesel + Battery Storage

System architecture

Wind turbine	14 WES 5 Tulipo
Generator 1	25 kW
Battery	270 Surrette S460
Inverter	40 kW
Rectifier	40 kW
Dispatch strategy	Cycle Charging

Cost summary

Total net present cost	$ 730,709
Levelized cost of energy	$ 0.417/kWh
Operating cost	$ 36,253/yr



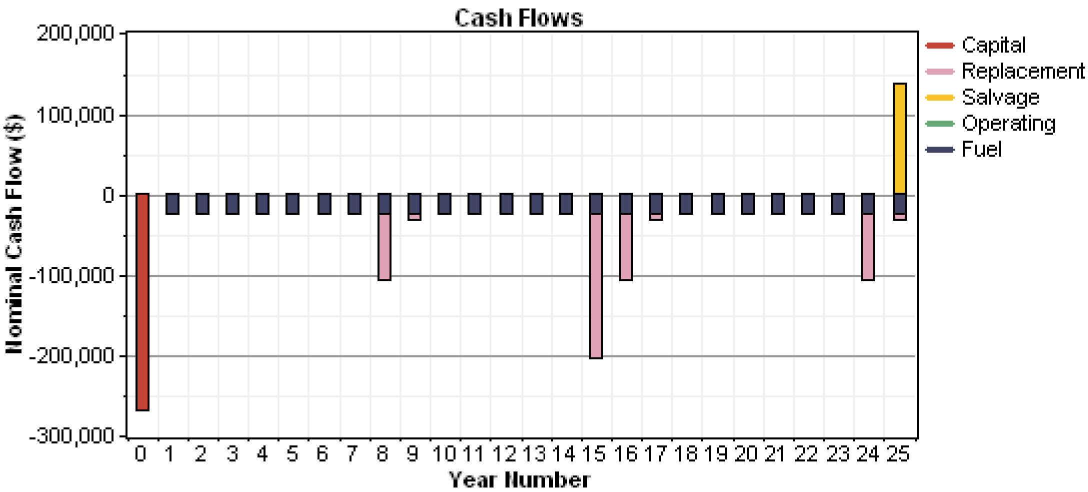
Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)

WES 5 Tulipo	175,000	73,021	0	0	-13,592	234,430
Generator 1	6,627	8,368	1,590	307,647	-1,376	322,855
Surrette S460	81,000	102,711	0	0	-16,514	167,197
Converter	4,648	1,940	0	0	-361	6,227
System	267,275	186,041	1,590	307,647	-31,843	730,709

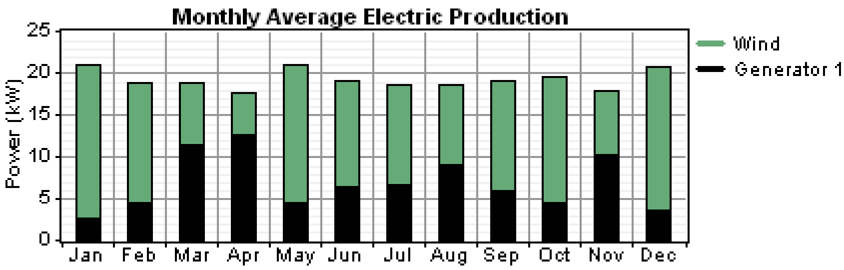
Annualized Costs

Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
WES 5 Tulipo	13,690	5,712	0	0	-1,063	18,339
Generator 1	518	655	124	24,066	-108	25,256
Surrette S460	6,336	8,035	0	0	-1,292	13,079
Converter	364	152	0	0	-28	487
System	20,908	14,553	124	24,066	-2,491	57,161



Electrical

Component	Production (kWh/yr)	Fraction
Wind turbines	107,893	64%
Generator 1	60,325	36%
Total	168,217	100%



Load	Consumption	Fraction
	(kWh/yr)	
AC primary load	124,465	91%
Deferrable load	12,714	9%
Total	137,179	100%

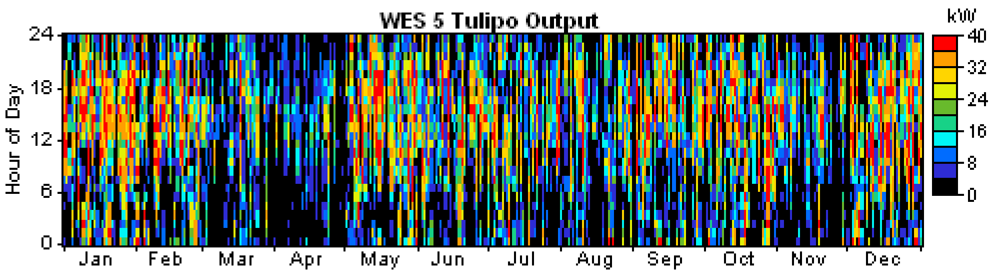
Quantity	Value	Units
Excess electricity	11,168	kWh/yr
Unmet load	6.49	kWh/yr
Capacity shortage	6.49	kWh/yr
Renewable fraction	0.641	

AC Wind Turbine: WES 5 Tulipo

Variable	Value	Units
Total rated capacity	35.0	kW
Mean output	12.3	kW
Capacity factor	35.2	%
Total production	107,893	kWh/yr

Minimum output	0.00	kW
Maximum output	36.7	kW
Wind penetration	86.7	%
Hours of operation	7,904	hr/yr
Levelized cost	0.170	$/kWh

Variable	Value	Units



Generator 1

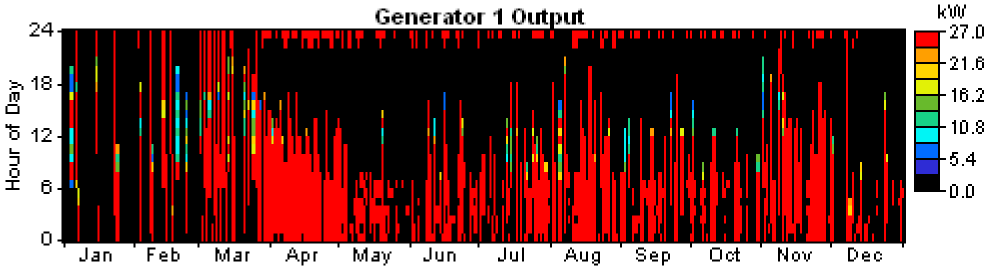
Quantity	Value	Units
Hours of operation	2,487	hr/yr
Number of starts	292	starts/yr
Operational life	8.04	yr
Capacity factor	27.5	%
Fixed generation cost	2.78	$/hr

Marginal generation cost	0.300	$/kWhyr

Quantity	Value	Units
Electrical production	60,325	kWh/yr
Mean electrical output	24.3	kW
Min. electrical output	7.50	kW
Max. electrical output	25.0	kW

Quantity	Value	Units

Fuel consumption	20,055	L/yr
Specific fuel consumption	0.332	L/kWh
Fuel energy input	197,343	kWh/yr
Mean electrical efficiency	30.6	%



Battery

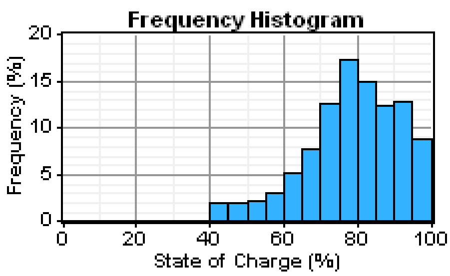
Quantity	Value
String size	1
Strings in parallel	270

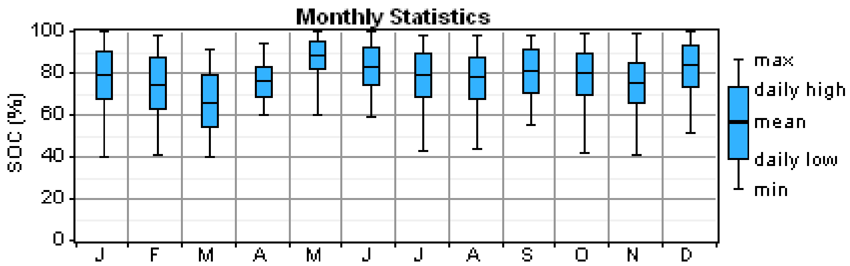
Batteries	270
Bus voltage (V)	6

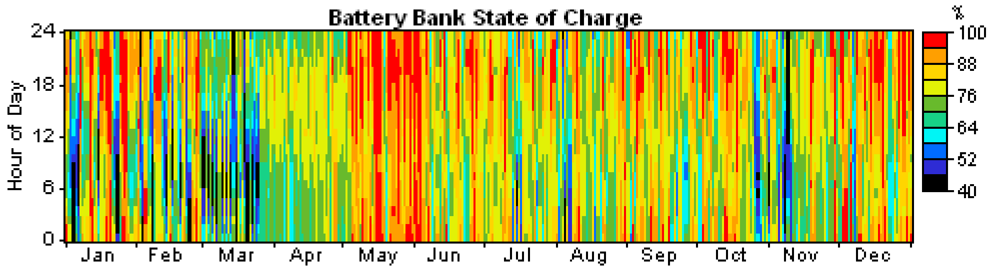
Quantity	Value	Units
Nominal capacity	745	kWh
Usable nominal capacity	447	kWh
Autonomy	28.5	hr
Lifetime throughput	376,380	kWh
Battery wear cost	0.241	$/kWh
Average energy cost	0.151	$/kWh

Quantity	Value	Units
Energy in	47,864	kWh/yr
Energy out	38,358	kWh/yr
Storage depletion	76.2	kWh/yr
Losses	9,430	kWh/yr
Annual throughput	42,886	kWh/yr

Expected life	8.00	yr



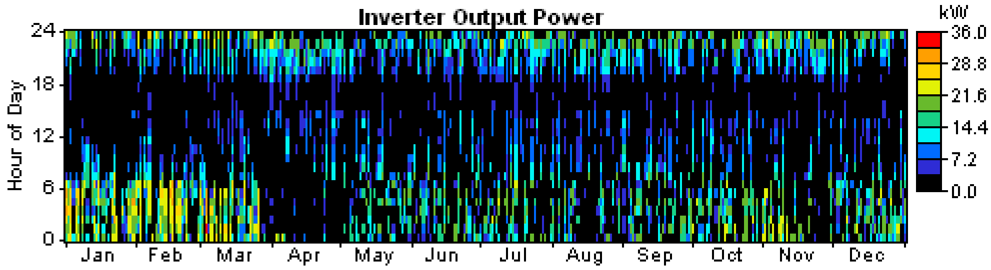


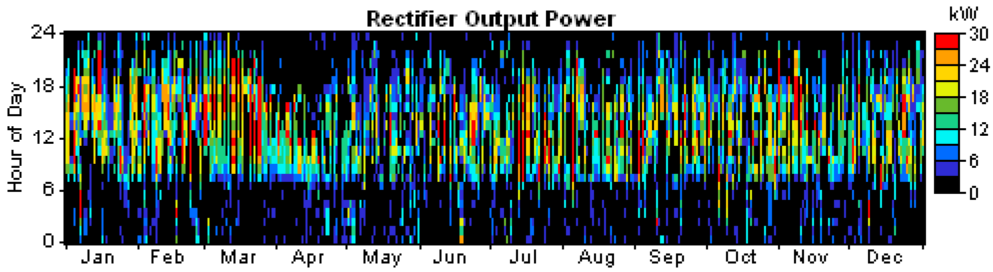


Converter

Quantity	Inverter	Rectifier	Units
Capacity	40.0	40.0	kW
Mean output	4.2	5.5	kW
Minimum output	0.0	0.0	kW
Maximum output	33.5	29.2	kW
Capacity factor	10.4	13.7	%

Quantity	Inverter	Rectifier	Units
Hours of operation	3,623	4,732	hrs/yr
Energy in	38,358	56,311	kWh/yr
Energy out	36,440	47,864	kWh/yr
Losses	1,918	8,447	kWh/yr





Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	52,812
Carbon monoxide	130
Unburned hydocarbons	14.4
Particulate matter	9.83
Sulfur dioxide	106
Nitrogen oxides	1,163

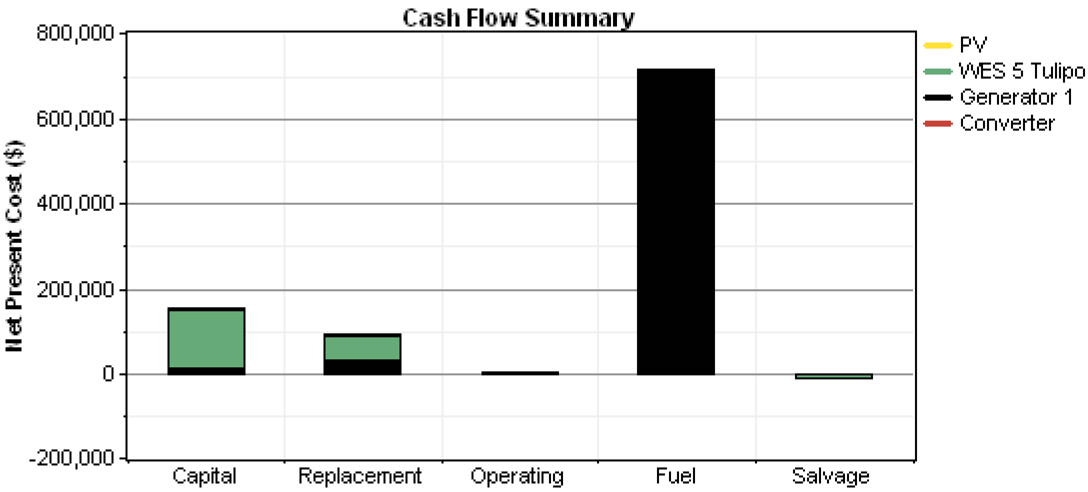
C2- 8: System Report – PV + Wind + Diesel

System architecture

PV Array	1 kW
Wind turbine	11 WES 5 Tulipo
Generator 1	35 kW
Inverter	40 kW
Rectifier	40 kW

Cost summary

Total net present cost	$ 952,432
Levelized cost of energy	$ 0.543/kWh
Operating cost	$ 62,342/yr

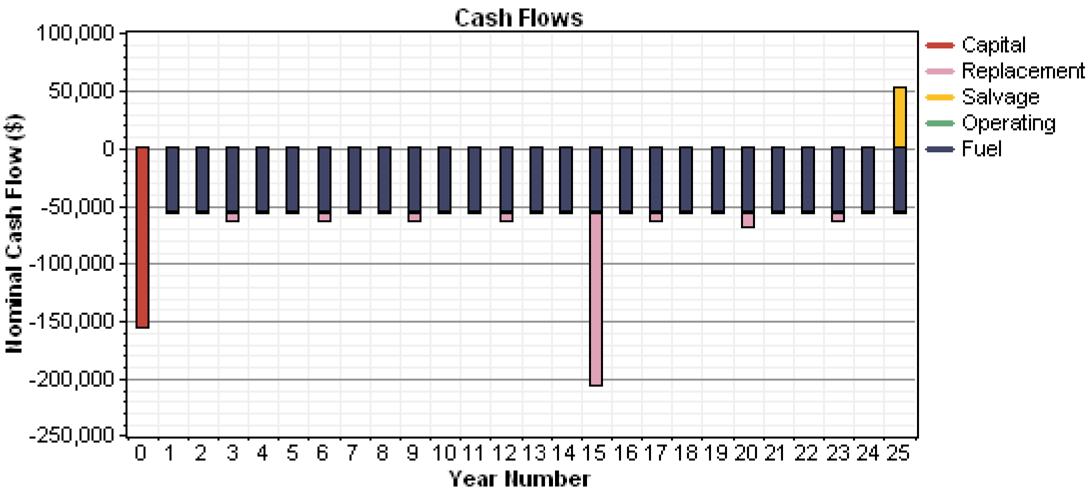


Net Present Costs

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	6,000	1,871	0	0	-1,048	6,822
WES 5 Tulipo	137,500	57,374	0	0	-10,679	184,195
Generator 1	7,343	30,137	4,549	713,337	-178	755,189
Converter	4,648	1,940	0	0	-361	6,227
System	155,492	91,322	4,549	713,337	-12,266	952,433

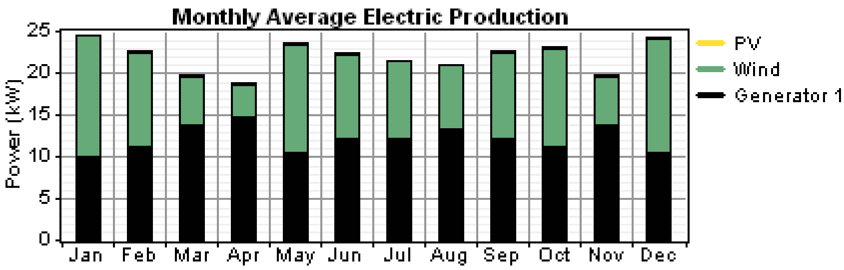
Annualized Costs

Component	**Capital** ($/yr)	**Replacement** ($/yr)	**O&M** ($/yr)	**Fuel** ($/yr)	**Salvage** ($/yr)	**Total** ($/yr)
PV	469	146	0	0	-82	534
WES 5 Tulipo	10,756	4,488	0	0	-835	14,409
Generator 1	574	2,358	356	55,802	-14	59,076
Converter	364	152	0	0	-28	487
System	12,164	7,144	356	55,802	-960	74,506



Electrical

Component	Production (kWh/yr)	Fraction
PV array	1,555	1%
Wind turbines	84,773	44%
Generator 1	106,289	55%
Total	192,617	100%



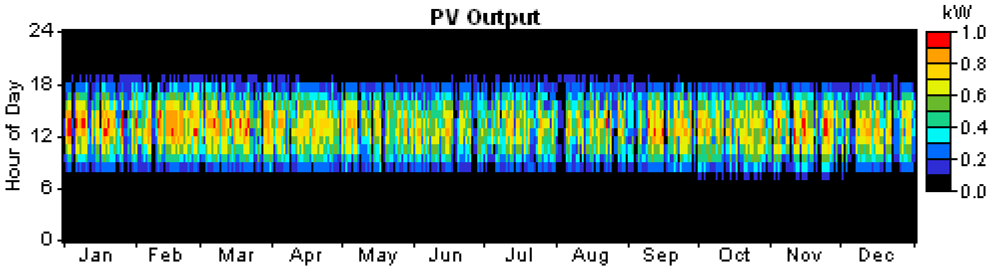
Load	**Consumption** (kWh/yr)	**Fraction**
AC primary load	124,464	91%
Deferrable load	12,729	9%
Total	137,194	100%

Quantity	**Value**	**Units**
Excess electricity	55,418	kWh/yr
Unmet load	0.588	kWh/yr
Capacity shortage	7.42	kWh/yr
Renewable fraction	0.448	

PV

Quantity	Value	Units
Rated capacity	1.00	kW
Mean output	0.178	kW
Mean output	4.26	kWh/d
Capacity factor	17.8	%
Total production	1,555	kWh/yr

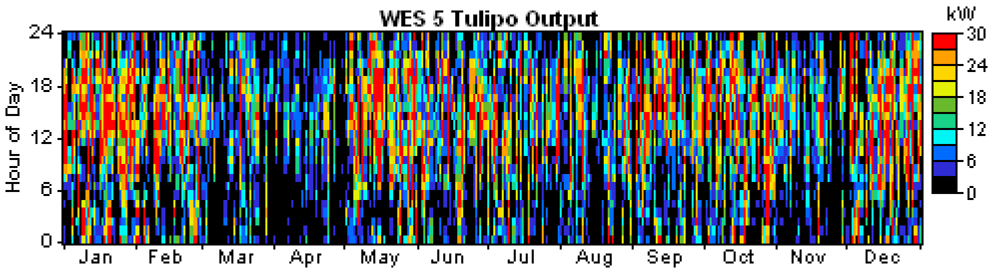
Quantity	**Value**	**Units**
Minimum output	0.00	kW
Maximum output	0.970	kW
PV penetration	1.25	%
Hours of operation	4,380	hr/yr
Levelized cost	0.343	$/kWh

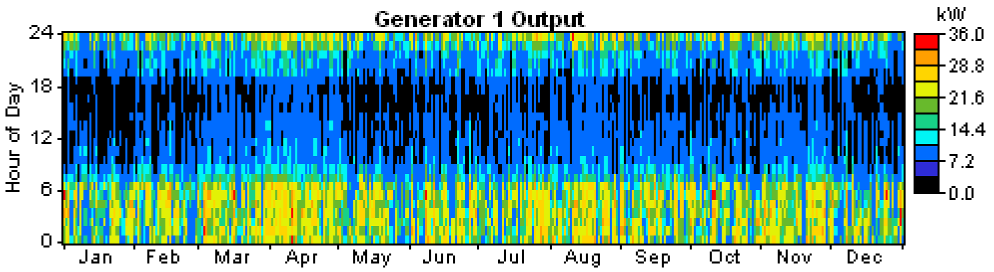


AC Wind Turbine: WES 5 Tulipo

Variable	**Value**	**Units**
Total rated capacity	27.5	kW
Mean output	9.68	kW
Capacity factor	35.2	%
Total production	84,773	kWh/yr

Variable	**Value**	**Units**
Minimum output	0.00	kW
Maximum output	28.9	kW
Wind penetration	68.1	%
Hours of operation	7,904	hr/yr
Levelized cost	0.170	$/kWh





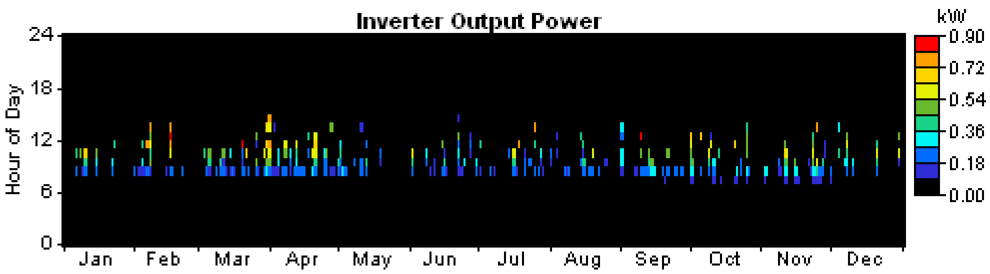
Generator 1

Quantity	Value	Units
Hours of operation	7,117	hr/yr
Number of starts	414	starts/yr
Operational life	2.81	yr
Capacity factor	34.7	%
Fixed generation cost	3.78	$/hr
Marginal generation cost	0.300	$/kWhyr

Quantity	Value	Units
Electrical production	106,289	kWh/yr
Mean electrical output	14.9	kW
Min. electrical output	10.5	kW
Max. electrical output	35.0	kW

Converter

Quantity	Inverter	Rectifier	Units
Hours of operation	572	0	hrs/yr
Energy in	119	0	kWh/yr
Energy out	113	0	kWh/yr
Losses	6	0	kWh/yr



Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	122,454
Carbon monoxide	302
Unburned hydocarbons	33.5
Particulate matter	22.8
Sulfur dioxide	246
Nitrogen oxides	2,697

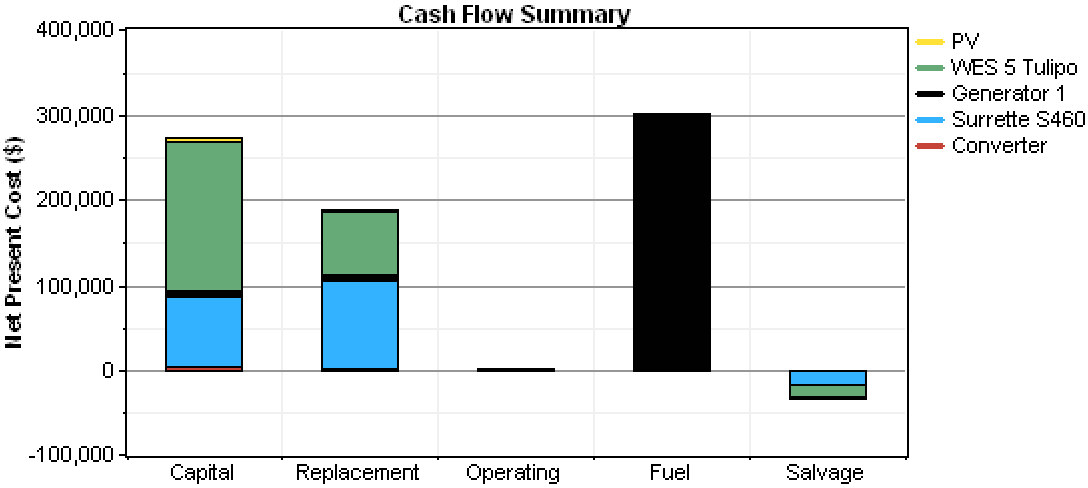
C2-9: System Report – PV + Wind + Diesel + Battery Storage

System architecture

PV Array	1 kW
Wind turbine	14 WES 5 Tulipo
Generator 1	25 kW
Battery	270 Surrette S460
Inverter	40 kW
Rectifier	40 kW
Dispatch strategy	Cycle Charging

Cost summary

Total net present cost	$ 730,771
Levelized cost of energy	$ 0.417/kWh
Operating cost	$ 35,788/yr

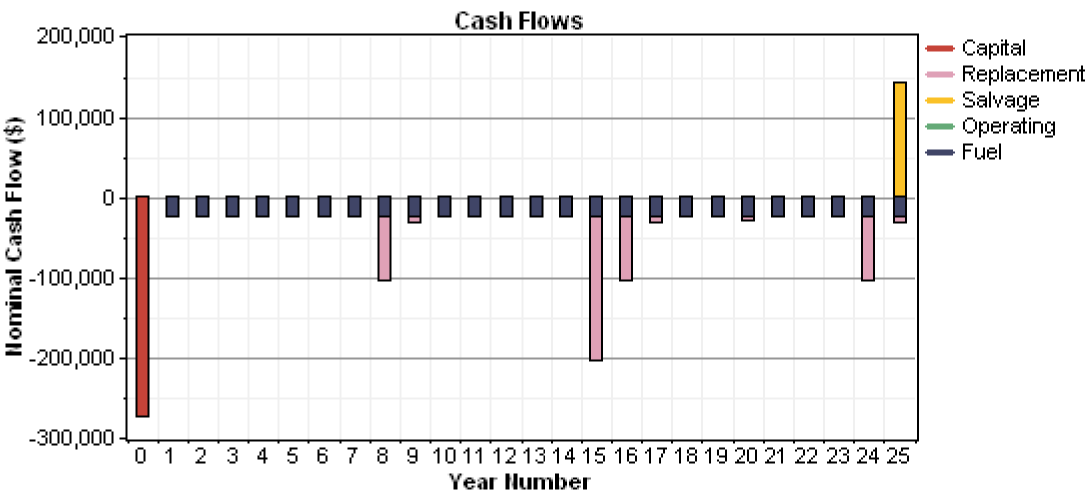


Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)
PV	6,000	1,871	0	0	-1,048	6,822
WES 5 Tulipo	175,000	73,021	0	0	-13,592	234,430
Generator 1	6,627	8,225	1,556	301,165	-1,478	316,094
Surrette S460	81,000	102,711	0	0	-16,514	167,197
Converter	4,648	1,940	0	0	-361	6,227
System	273,275	187,768	1,556	301,165	-32,993	730,771

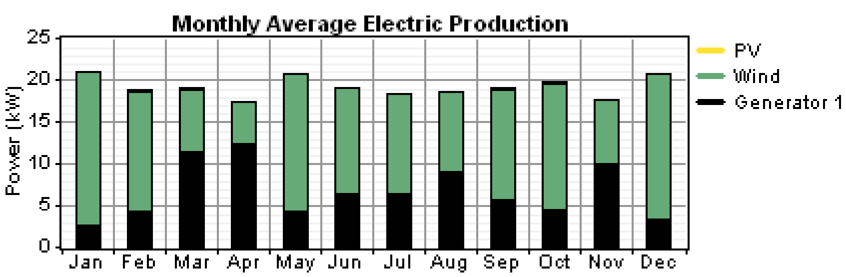
Annualized Costs

Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	469	146	0	0	-82	534
WES 5 Tulipo	13,690	5,712	0	0	-1,063	18,339
Generator 1	518	643	122	23,559	-116	24,727
Surrette S460	6,336	8,035	0	0	-1,292	13,079
Converter	364	152	0	0	-28	487
System	21,377	14,688	122	23,559	-2,581	57,166



Electrical

Component	Production (kWh/yr)	Fraction
PV array	1,555	1%
Wind turbines	107,893	64%
Generator 1	59,059	35%
Total	168,506	100%



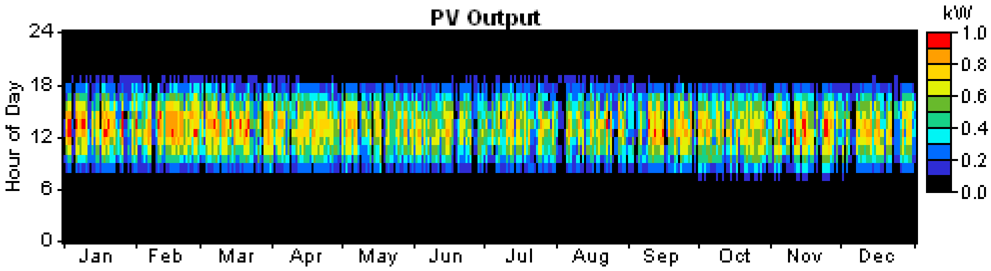
Load	Consumption	Fraction
	(kWh/yr)	
AC primary load	124,465	91%
Deferrable load	12,714	9%
Total	137,179	100%

Quantity	Value	Units
Excess electricity	11,334	kWh/yr
Unmet load	5.48	kWh/yr
Capacity shortage	6.13	kWh/yr
Renewable fraction	0.650	

PV

Quantity	Value	Units
Rated capacity	1.00	kW
Mean output	0.178	kW
Mean output	4.26	kWh/d
Capacity factor	17.8	%
Total production	1,555	kWh/yr

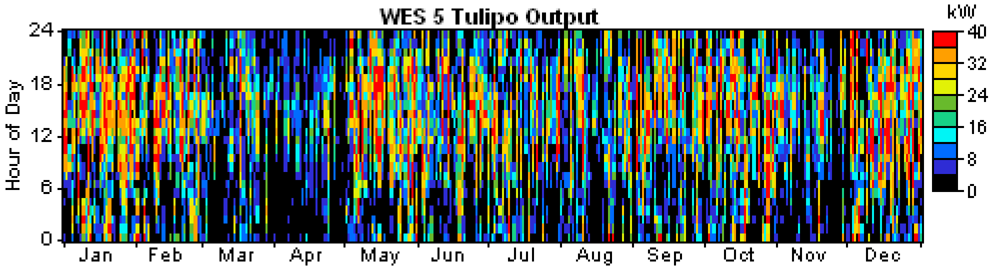
Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	0.970	kW
PV penetration	1.25	%
Hours of operation	4,380	hr/yr
Levelized cost	0.343	$/kWh



AC Wind Turbine: WES 5 Tulipo

Variable	Value	Units
Total rated capacity	35.0	kW
Mean output	12.3	kW
Capacity factor	35.2	%
Total production	107,893	kWh/yr

Variable	Value	Units
Minimum output	0.00	kW
Maximum output	36.7	kW
Wind penetration	86.7	%
Hours of operation	7,904	hr/yr
Levelized cost	0.170	$/kWh

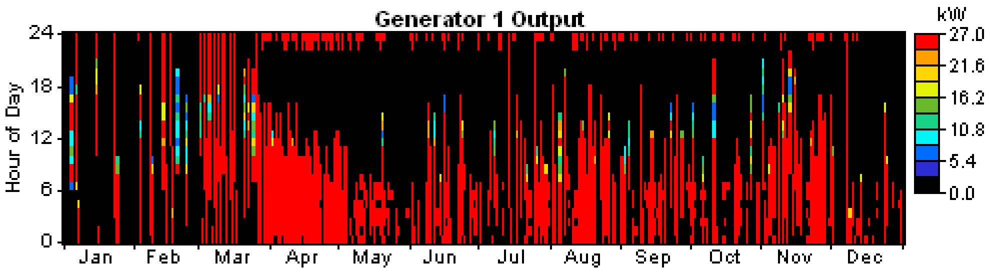


Quantity	Value	Units
Electrical production	59,059	kWh/yr
Mean electrical output	24.3	kW
Min. electrical output	7.50	kW
Max. electrical output	25.0	kW

Generator 1

Quantity	Value	Units
Hours of operation	2,434	hr/yr
Number of starts	277	starts/yr
Operational life	8.22	yr
Capacity factor	27.0	%
Fixed generation cost	2.78	$/hr
Marginal generation cost	0.300	$/kWhyr

Quantity	Value	Units
Fuel consumption	19,633	L/yr
Specific fuel consumption	0.332	L/kWh
Fuel energy input	193,185	kWh/yr
Mean electrical efficiency	30.6	%

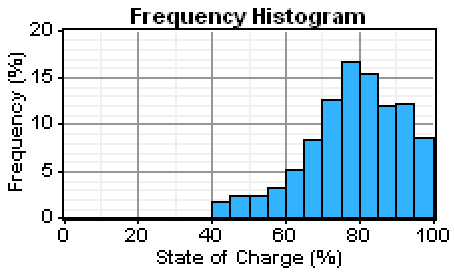


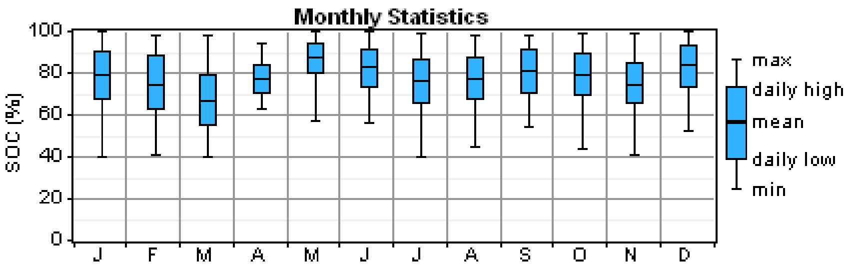
Battery

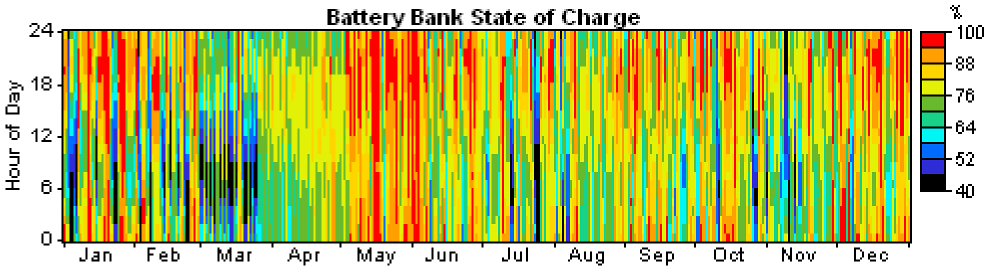
Quantity	Value
String size	1
Strings in parallel	270
Batteries	270
Bus voltage (V)	6

Quantity	Value	Units
Nominal capacity	745	kWh
Usable nominal capacity	447	kWh
Autonomy	28.5	hr
Lifetime throughput	376,380	kWh
Battery wear cost	0.241	$/kWh
Average energy cost	0.149	$/kWh

Quantity	Value	Units
Energy in	48,622	kWh/yr
Energy out	38,982	kWh/yr
Storage depletion	96.5	kWh/yr
Losses	9,543	kWh/yr
Annual throughput	43,583	kWh/yr
Expected life	8.00	yr



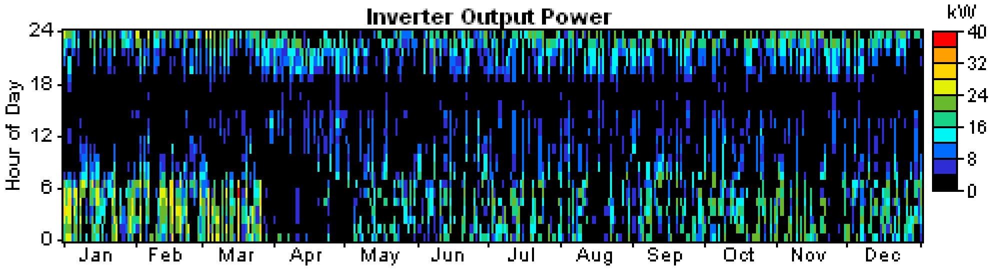


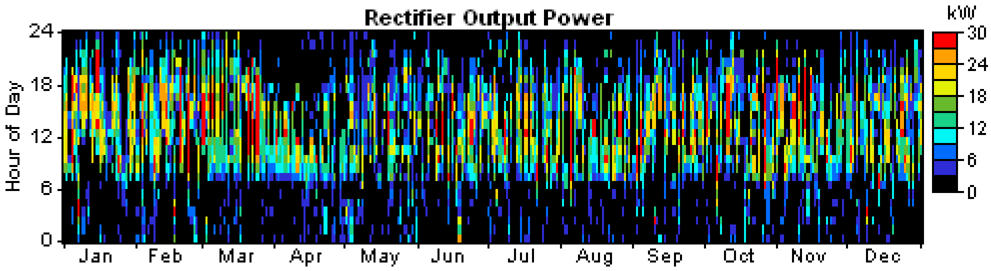


Converter

Quantity	Inverter	Rectifier	Units
Capacity	40.0	40.0	kW
Mean output	4.3	5.4	kW
Minimum output	0.0	0.0	kW
Maximum output	37.5	29.2	kW
Capacity factor	10.7	13.6	%

Quantity	Inverter	Rectifier	Units
Hours of operation	3,760	4,720	hrs/yr
Energy in	39,416	55,883	kWh/yr
Energy out	37,445	47,501	kWh/yr
Losses	1,971	8,382	kWh/yr





Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	51,699
Carbon monoxide	128
Unburned hydocarbons	14.1
Particulate matter	9.62
Sulfur dioxide	104
Nitrogen oxides	1,139

Appendix D: System Suitability Index

The system suitability factor, **Λ** has been calculated for the systems in the following tables and mainly two price scenarios for the renewable components have been considered:

Low price: Wind systems at 3.5 $/W and PV at 4.21$/W

High price: Wind systems at 5 $/W and PV at 6 $/W

The following colour code has been used for easy identification of system suitability. Table 7.12 explains how the number ranges are classified.

Λ	**$\Lambda<0.5$**	**$0.5<\Lambda<1$**	**$1<\Lambda<5$**	**$5<\Lambda<15$**	**$15<\Lambda$**

Table D-1 Suitability factors for low price scenario

	Low Prices Hypothesis					
	1st LC			2nd LC		3rd LC
System Composition	0%	5%	15%	0%	5%	0%
Wind turbines, batteries WES 5 Tulipo (2.5kW) Surette S460 (2.76kWh)	11.66	3.33	1.19	-	5.36	-
Wind turbines, batteries SW Whisper 500 (3kW) Surette S460 (2.76kWh)	18.73	5.25	1.99	-	8.57	-
Wind turbines, batteries BWC Excel-R (7.5kW) Surette S460 (2.76kWh)	74.56	19.26	5.99	-	18.56	-
Wind turbines, batteries BWC Excel-S (10kW) Surette S460 (2.76kWh)	206.3	58.84	17.55	-	56.69	219.19
PV, batteries Surette S460 (2.76kWh)	6.86	3.92	3.83	6.99	3.99	7.72
One Diesel Generator 1$/L	1.63	1.31	1.44	1.68	1.5	2.37
One Diesel Generator 1.2$/L	1.63	1.31	1.45	1.66	1.5	2.34
Two Diesel Generators 1$/L	1.34	1.28	1.37	1.33	1.36	1.56
Two Diesel Generators 1.2$/L	1.34	1.28	1.36	1.32	1.33	1.51
One Diesel Generator, batteri 1$/L Surette S460 (2.76kWh)	1.33	1.3	1.38	2.62	2.76	2.74
One Diesel Generator, batteri 1.2$/L Surette S460 (2.76kWh)	1.32	1.3	1.38	2.36	2.48	2.46
Two Diesel Generators, batter 1$/L Surette S460 (2.76kWh)	1.26	1.31	1.43	2.56	2.78	2.73

Table D-1 Suitability factors for low price scenario (Continuation...)

	Low Prices Hypothesis					
	1st LC			2nd LC		3rd LC
Two Diesel Generators, batteries 1.2$/L Surette S460 (2.76kWh)	1.25	1.3	1.41	2.28	2.48	2.41
Wind turbines, PV, batteries WES 5 Tulipo (2.5kW) Surette S460 (2.76kWh)	2.88	1.5	0.81	2.94	1.48	3.28
Wind turbines, PV, batteries SW Whisper 500 (3kW) Surette S460 (2.76kWh)	3.66	1.94	1.2	3.68	1.96	4.07
Wind turbines, PV, batteries BWC Excel-R (7.5kW) Surette S460 (2.76kWh)	5.09	2.85	2.13	5.31	2.85	5.8
Wind turbines, PV, batteries BWC Excel-S (10kW) Surette S460 (2.76kWh)	6.27	3.57	2.98	6.55	3.62	7.08
Wind turbines, Diesel generator WES 5 Tulipo (2.5kW) 1$/L Surette S460 (2.76kWh)	0.52	0.58	0.42	0.18	0.23	0.37
Wind turbines, Diesel generator WES 5 Tulipo (2.5kW) 1.2$/L Surette S460 (2.76kWh)	0.37	0.42	0.35	0.12	0.16	0.18
Wind turbines, Diesel generator SW Whisper 500 (3kW) 1$/L Surette S460 (2.76kWh)	0.84	0.89	0.61	0.84	0.38	0.87
Wind turbines, Diesel generator SW Whisper 500 (3kW) 1.2$/L Surette S460 (2.76kWh)	0.55	0.63	0.55	0.21	0.26	0.56
Wind turbines, Diesel generator BWC Excel-R (7.5kW) 1$/L Surette S460 (2.76kWh)	2.47	3.03	3.27	1.73	1.49	2.11
Wind turbines, Diesel generator BWC Excel-R (7.5kW) 1.2$/L Surette S460 (2.76kWh)	1.67	2.34	2.88	0.97	0.5	1.51

Table D-1 Suitability factors for low price scenario (Continuation...)

	Low Prices Hypothesis					
	1st LC			2nd LC		3rd LC
Wind turbines, Diesel generator, batteries BWC Excel-S (10kW) 1$/L Surette S460 (2.76kWh)	1.33	1.33	1.28	18.88	19.62	13.96
Wind turbines, Diesel generator, batteries BWC Excel-S (10kW) 1.2$/L Surette S460 (2.76kWh)	4.66	4.91	14.76	9.92	5.21	4.96
PV, Diesel generator, batteries 1$/L Surette S460 (2.76kWh)	3.94	9.47	26.31	3.12	2.9	3.42
PV, Diesel generator, batteries 1.2$/L Surette S460 (2.76kWh)	3.2	3.37	7.33	2.44	1.99	2.85
Wind turbines, PV, Diesel generator, batteries WES 5 Tulipo (2.5kW) 1$/L Surette S460 (2.76kWh)	0.54	0.58	0.16	0.19	0.11	0.37
Wind turbines, PV, Diesel generator, batteries WES 5 Tulipo (2.5kW) 1.2$/L Surette S460 (2.76kWh)	0.38	0.15	0.1	0.12	0.07	0.18
Wind turbines, PV, Diesel generator, batteries SW Whisper 500 (3kW) 1$/L Surette S460 (2.76kWh)	0.91	0.92	1.01	0.73	0.23	0.64
Wind turbines, PV, Diesel generator, batteries SW Whisper 500 (3kW) 1.2$/L Surette S460 (2.76kWh)	0.54	0.23	0.15	0.21	0.13	0.49
Wind turbines, PV, Diesel generator, batteries BWC Excel-R (7.5kW) 1$/L Surette S460 (2.76kWh)	1.92	3.73	4.3	1.1	2.02	1.47
Wind turbines, PV, Diesel generator, batteries BWC Excel-R (7.5kW) 1.2$/L Surette S460 (2.76kWh)	1.35	1.65	1.96	0.78	0.3	1.07

Table D-1 Suitability factors for low price scenario (Continuation...)

	Low Prices Hypothesis					
	1st LC			2nd LC		3rd LC
Wind turbines, PV, Diesel generat BWC Excel-S (10kW) 1$/L Surette S460 (2.76kWh)	3.94	24.74	8.37	2.97	3.13	3.42
Wind turbines, PV, Diesel generat BWC Excel-S (10kW) 1.2$/L Surette S460 (2.76kWh)	2.87	3.02	7.95	2.12	0.86	2.4
Wind turbines, PV, Diesel generat WES 5 Tulipo (2.5kW) 1$/L Surette S460 (2.76kWh)	4.4	0.7	0.48	1.17	0.9	1.95
Wind turbines, PV, Diesel generat WES 5 Tulipo (2.5kW) 1.2$/L Surette S460 (2.76kWh)	0.65	0.53	0.4	0.87	0.67	1.77
Wind turbines, PV, Diesel generat SW Whisper 500 (3kW) 1$/L Surette S460 (2.76kWh)	8.49	5.32	3.63	2.68	2.57	3.85
Wind turbines, PV, Diesel generat SW Whisper 500 (3kW) 1.2$/L Surette S460 (2.76kWh)	6.17	3.15	3.06	1.63	1.32	2.85
Wind turbines, PV, Diesel generat BWC Excel-R (7.5kW) 1$/L Surette S460 (2.76kWh)	10.82	14.61	4.03	1.68	5.51	6.58
Wind turbines, PV, Diesel generat BWC Excel-R (7.5kW) 1.2$/L Surette S460 (2.76kWh)	9.54	9.05	3.73	2.75	2.38	5.68
Wind turbines, PV, Diesel generat BWC Excel-S (10kW) 1$/L Surette S460 (2.76kWh)	11.4	15.32	1.35	1.68	7.07	6.58
Wind turbines, PV, Diesel generat BWC Excel-S (10kW) 1.2$/L Surette S460 (2.76kWh)	10.93	13	3.65	4.74	2.52	5.68

Table D-2 Suitability factors for high price scenario

	High Prices Hypothesis					
	1st LC			2nd LC		3rd LC
System Composition	0%	5%	15%	0%	5%	0%
Wind turbines, batteries WES 5 Tulipo (2.5k Surette S460 (2.76k	33.04	6.83	2.4	-	8.99	-
Wind turbines, batteries SW Whisper 500 (3k Surette S460 (2.76k	32.68	11.21	4.16	-	14.55	-
Wind turbines, batteries BWC Excel-R (7.5k Surette S460 (2.76k	155.16	40.41	12.68	-	38.64	127.44
Wind turbines, batteries BWC Excel-S (10kW Surette S460 (2.76k	600.83	186.61	40.72	-	117.06	445.12
PV, batteries Surette S460 (2.76k	12.88	7.84	7.52	13.08	8.05	14.81
One Diesel Generator 1$/L	1.63	1.31	1.44	1.68	1.5	2.37
One Diesel Generator 1.2$/L	1.63	1.31	1.45	1.66	1.5	2.34
Two Diesel Generators 1$/L	1.34	1.28	1.37	1.33	1.36	1.56
Two Diesel Generators 1.2$/L	1.34	1.28	1.36	1.32	1.33	1.51
One Diesel Generator, ba 1$/L Surette S460 (2.76k	1.33	1.3	1.38	2.62	2.76	2.74
One Diesel Generator, ba 1.2$/L Surette S460 (2.76k	1.32	1.3	1.38	2.36	2.48	2.46
Two Diesel Generators, b 1$/L Surette S460 (2.76k	1.26	1.31	1.43	2.56	2.78	2.73

Table D-2 Suitability factors for high price scenario (continuation…)

	High Prices Hypothesis					
	1st LC			2nd LC		3rd LC
System Composition	0%	5%	15%	0%	5%	0%
Two Diesel Generators, batterie 1.2$/L Surette S460 (2.76kWh)	1.25	1.3	1.41	2.28	2.48	2.41
Wind turbines, PV, batteries WES 5 Tulipo (2.5kW) Surette S460 (2.76kWh)	6.27	3.27	1.73	6.3	3.19	6.83
Wind turbines, PV, batteries SW Whisper 500 (3kW) Surette S460 (2.76kWh)	6.01	3.11	1.54	7.72	4.22	8.54
Wind turbines, PV, batteries BWC Excel-R (7.5kW) Surette S460 (2.76kWh)	10.02	6.02	4.58	10.61	5.99	11.21
Wind turbines, PV, batteries BWC Excel-S (10kW) Surette S460 (2.76kWh)	12.26	7.49	6.41	12.5	7.53	13.47
Wind turbines, Diesel generato WES 5 Tulipo (2.5kW) 1$/L Surette S460 (2.76kWh)	0.95	1.02	1.04	0.81	0.45	0.95
Wind turbines, Diesel generato WES 5 Tulipo (2.5kW) 1.2$/L Surette S460 (2.76kWh)	0.79	0.76	0.52	0.2	0.29	0.53
Wind turbines, Diesel generato SW Whisper 500 (3kW) 1$/L Surette S460 (2.76kWh)	1.91	1.83	1.72	1.45	1.81	1.54
Wind turbines, Diesel generato SW Whisper 500 (3kW) 1.2$/L Surette S460 (2.76kWh)	1.34	1.44	2.26	0.82	0.57	1.25
Wind turbines, Diesel generato BWC Excel-R (7.5kW) 1$/L Surette S460 (2.76kWh)	5.32	15.1	29.74	3.05	35.09	11.8
Wind turbines, Diesel generato BWC Excel-R (7.5kW) 1.2$/L Surette S460 (2.76kWh)	3.79	5.04	7.34	2.05	3.08	3.77

Table D-2 Suitability factors for high price scenario (continuation…)

	High Prices Hypothesis					
	1st LC			2nd LC		3rd LC
System Composition	0%	5%	15%	0%	5%	0%
Wind turbines, Diesel generator, BWC Excel-S (10kW) 1$/L Surette S460 (2.76kWh)	1.33	1.33	1.28	2.61	2.75	2.74
Wind turbines, Diesel generator, BWC Excel-S (10kW) 1.2$/L Surette S460 (2.76kWh)	1.32	1.32	2.14	2.33	18.5	2.46
PV, Diesel generator, batteries 1$/L Surette S460 (2.76kWh)	1.33	132.14	1.43	11.28	31.57	9.19
PV, Diesel generator, batteries 1.2$/L Surette S460 (2.76kWh)	4.76	130.02	45.21	4.29	4.52	5.38
Wind turbines, PV, Diesel genera WES 5 Tulipo (2.5kW) 1$/L Surette S460 (2.76kWh)	0.95	1.1	1.16	0.77	0.45	0.84
Wind turbines, PV, Diesel genera WES 5 Tulipo (2.5kW) 1.2$/L Surette S460 (2.76kWh)	0.79	0.76	0.36	0.33	0.31	0.61
Wind turbines, PV, Diesel genera SW Whisper 500 (3kW) 1$/L Surette S460 (2.76kWh)	1.45	1.72	1.67	1.45	1.81	1.54
Wind turbines, PV, Diesel genera SW Whisper 500 (3kW) 1.2$/L Surette S460 (2.76kWh)	1.11	1.3	1.42	0.82	0.57	1.01
Wind turbines, PV, Diesel genera BWC Excel-R (7.5kW) 1$/L Surette S460 (2.76kWh)	1.33	15.1	1.43	5.06	3.36	8
Wind turbines, PV, Diesel genera BWC Excel-R (7.5kW) 1.2$/L Surette S460 (2.76kWh)	3.59	5.04	4.58	1.99	2.35	3.18

Table D-2 Suitability factors for high price scenario (continuation…)

	High Prices Hypothesis					
	1st LC			2nd LC		3rd LC
System Composition	0%	5%	15%	0%	5%	0%
Wind turbines, PV, Diesel genera BWC Excel-S (10kW) 1$/L Surette S460 (2.76kWh)	1.33	132.14	1.43	11.28	31.57	9.19
Wind turbines, PV, Diesel genera BWC Excel-S (10kW) 1.2$/L Surette S460 (2.76kWh)	4.76	64.35	26.57	4.29	4.52	5.38
Wind turbines, PV, Diesel genera WES 5 Tulipo (2.5kW) 1$/L Surette S460 (2.76kWh)	9.2	27.8	6.15	3.49	2.67	3.78
Wind turbines, PV, Diesel genera WES 5 Tulipo (2.5kW) 1.2$/L Surette S460 (2.76kWh)	6.55	35.57	6.21	1.67	1.85	2.98
Wind turbines, PV, Diesel genera SW Whisper 500 (3kW) 1$/L Surette S460 (2.76kWh)	10.02	24.34	4.43	1.68	7.75	2.69
Wind turbines, PV, Diesel genera SW Whisper 500 (3kW) 1.2$/L Surette S460 (2.76kWh)	9.68	8.2	3.88	1.66	7.34	2.67
Wind turbines, PV, Diesel genera BWC Excel-R (7.5kW) 1$/L Surette S460 (2.76kWh)	1.72	21.08	1.35	1.68	1.5	2.69
Wind turbines, PV, Diesel genera BWC Excel-R (7.5kW) 1.2$/L Surette S460 (2.76kWh)	11.28	20.58	4.22	1.66	1.46	2.67
Wind turbines, PV, Diesel genera BWC Excel-S (10kW) 1$/L Surette S460 (2.76kWh)	1.72	16.22	1.35	1.68	1.5	2.69
Wind turbines, PV, Diesel genera BWC Excel-S (10kW) 1.2$/L Surette S460 (2.76kWh)	1.72	15.79	1.36	1.66	1.5	2.67

Appendix E: Software Tools in Energy Modelling

E1. RETScreen

The “RETScreen Clean Energy Project Analysis Software” is a decision support tool developed with the contribution of numerous experts from government, industry, and academia by Natural Resources Canada in 1996 (National Resources Canada). The software is provided free-of-charge and can be used worldwide to evaluate energy production and savings, costs, emission reductions and the financial viability and risks for various types of ‘Renewable-energy and Energy-efficient Technologies’ (RETs). Approximately 1,000 people download the tool every week; the total number of downloads so far is just under 250,000 (National Resources Canada). Fundamental to RETScreen is a comparison between a ‘base case’, typically the conventional technology, and a ‘proposed case’, which typically involves clean energy technology. The comparison includes all costs and a number of economic indices i.e. internal rate of return (IRR) and net present value (NPV) (Connolly et al. 2010). RETScreen is ultimately not concerned with the absolute costs, but rather the costs of the proposed case that are in excess of those for the base case. If, for example, a proposed on-grid wind farm generates 50,000 MWh per year, then this is compared to the 50,000 MWh of electricity from conventional sources available through the grid. In a typical scenario, the base and proposed cases will have different costs associated with them: the proposed case will have higher initial costs and lower annual costs (i.e. savings). The software can be applied to any energy-system, ranging from individual projects to global applications. All thermal generation and renewable technologies can be accounted for using RETScreen; it can incorporate energy efficiency measures relatively easily. However, the only storage/conversion device considered is battery energy storage, which cannot model any transport technologies (Connolly et al. 2010).

RETScreen has been used in many energy projects all over the world. The following are some of the notable projects where RETScreen was extensively used:

- “Prospects of wind farm development in Algeria” (Himri et al. 2009). Here it was used to assess the energy output for a 30 MW installed capacity wind farm in Algeria in terms of gross energy, renewable energy delivered, specific yield and wind farm capacity factors.
- Feasibility of Solar thermal water heating in Lebanon (Houri 2006).
- Viability analysis of PV power plants in Egypt, where it was used to investigate, from techno-economical and environmental points of view, the sites in Egypt able to cope with a 10 MW PV-grid connected power plant (El-Shimy 2009).
- Techno economic assessment of a building-integrated PV system for electrical energy saving in residential sector (Bakos et al. 2003).
- Evaluation of region-specific residential energy systems for GHG(green house gas) reductions: Case studies in Canadian cities (Kikuchi et al. 2009).

E2. HOMER

HOMER is a user-friendly, micro-power design tool that was developed in 1992 by the National Renewable Energy Laboratory in the USA, who have released 42 versions of the program. It is free to download from (HOMER Energy LLC) (www.homerenergy.com), and since its release the HOMER software has been downloaded 150,000 times by 34,000 people in 193 countries. A typical analysis can be run after one day of training. "HOMER simulates and optimises stand-alone and grid-connected power systems with any combination of wind turbines, PV arrays, run-of-river hydro power, biomass power, internal combustion engine generators, micro turbines, fuel cells, batteries, and hydrogen storage, serving both electric and thermal loads (by individual or district-heating systems). Also, all costs (including any pollution penalties) except fuel handling costs and taxes are included" (Connolly et al. 2010). The minimum time step of one minute for a simulation for one year period is a typical output. HOMER's sensitivity analysis is essential in situations where data are uncertain. HOMER models both conventional and renewable energy technologies. The objective of the optimisation simulation is to evaluate the economic and technical feasibility of a large number of technology options, while considering variations in technology costs and energy resource availability.

Publications Relating to HOMER are available from the HOMER homepage, on which can be found articles describing HOMER, Peer-reviewed papers, Conference Papers, Theses and Dissertations, NREL Technical Papers and NREL White Papers.

Some projects that used HOMER for analysis are listed below:

- Assessment of the wind energy potential at different sites in Ethiopia (Bekele & Palm 2009)
- Feasibility study of hybrid retrofits to an isolated off-grid diesel power plant. This study was performed as a pre-feasibility analysis of wind penetration into an existing diesel plant of a village in north eastern part of Saudi Arabia (Rehman et al. 2007)

- A feasibility study of a zero energy home in Newfoundland where Energy system sizing is done to achieve a zero energy home (Iqbal 2004)
- Pre-feasibility study of the effects of using hybrid energy systems with hydrogen as an energy carrier for applications in Newfoundland, Canada (Khan & Iqbal 2005)
- HOMER has been used to simulate systems where up to 100% of the electricity and heat demand was met by renewable energy sources (Lambert et al. 2006)

E3. LEAP

LEAP (Long-range Energy Alternatives Planning) is an integrated modelling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. It can be used in both energy and non-energy sectors to take account of greenhouse gas (GHG) emission sources and sinks. LEAP was developed in 1980 in the USA and is currently maintained by the Stockholm Environment Institute (Connolly et al. 2010). It is free to qualified users in developing countries, but there is a cost for OECD (Organisation for Economic Co-operation and Development) based users. LEAP has been adopted by hundreds of organizations in more than 150 countries worldwide (in 169 countries by over 5,000 users, according to Connolly et al.). Its users include government agencies, academics, non-governmental organizations, consulting companies and energy utilities. It has been used at many different scales ranging from cities and states to national, regional and global applications and it takes typically three or four days of training to use the tool (online training is available in English, French, Spanish, Portuguese and Chinese).

Most studies use a forecast period of between 20 and 50 years. Some results are calculated with a finer level of temporal detail. LEAP functions using an annual time-step, and the time horizon can extend for an unlimited number of years. It supports a number of different modelling methodologies:

- On the demand-side these range from bottom-up, end-use accounting techniques to top-down macroeconomic modelling.
- On the supply side, it provides a range of accounting and simulation methodologies for modelling electricity generation and capacity expansion planning.

LEAP's modelling capabilities operate at two basic conceptual levels. On the first level, LEAP's built-in calculations handle all of the "non controversial" energy, emissions and cost-benefit accounting calculations. On the second level, users enter spreadsheet-like expressions that can be used to specify time-varying data or to create a wide variety of sophisticated multi-variable models, thus enabling econometric and simulation approaches to be embedded within LEAP's overall accounting framework. LEAP does not currently support optimization modelling, although this capability is currently being developed in conjunction with the IAEA in Vienna. Overall, LEAP can simulate all sectors, all technologies and all costs within an energy-system, as well as externalities for any pollutants, decommissioning costs and unmet demand costs. LEAP is designed around the concept of long-range scenario analysis. Scenarios are self-consistent storylines that explain how an energy system might evolve over time. Using LEAP, policy analysts can create and then evaluate alternative scenarios by comparing their energy requirements, their social costs and benefits and their environmental impacts. LEAP displays its results in charts, tables and maps, which are user-defined and can be exported to Excel or PowerPoint. The results include fuel demands, costs, unit productions, GHG emissions, air-pollutants and more. Usually, these results are then used to compare an active policy scenario versus a policy neutral business-as-usual scenario.

Forty four reports on the application of LEAP can be obtained from the home page (Stockholm Environment Institute) (www.energycommunity.org). LEAP has been used for over 70 peer-reviewed journal papers (Connolly et al. 2010).

Some examples of peer-reviewed papers where LEAP has been used for analysis include:

- Potential reductions in energy demand and GHG emissions in China's road transport sector (Yan & Crookes 2009)
- Sustainable power planning for the island of Crete in Greece (Giatrakos et al. 2009)
- Towards a low-carbon future in China's building sector—a review of energy and climate models forecast (Li 2008)

E4. energyPRO

energyPRO is a complete modelling software package for the combined techno-economic analysis and optimisation of both cogeneration and tri-generation projects and other types of complex energy projects with a combined supply of electricity and thermal energy from multiple different energy producing units. Detailed analyses of projects involving sources such as geothermal, solar collectors, photovoltaic or wind farms can also be carried out with the software. energyPRO can also be used for analyzing hydro pumping stations, compressed air energy storage and other electricity storage projects. It is developed and maintained by the company EMD International A/S in Denmark (EMD International A/S) and over 50 versions have been released over the past 20 years. This tool is not free and is available for between €2700-€5600, depending on the modules chosen and currently there are more than 1000 users in 16 countries (Connolly et al. 2010). One day of training is all that is necessary to be able to use energyPRO.

The energyPRO tool is specifically designed for a single thermal or CHP power-plant investigation. It can model all types of thermal generation except nuclear, all renewable generation and all energy storage units to complete the analysis. This tool only models district heating in the heating sector and does not include transport technologies. The analysis is carried out using a one-minute time-step for a maximum duration of 40 years (which represents the typical lifetime of a power-plant). energyPRO is also superior for regional energy planning analyses, as it is possible to combine an unlimited number of different types of geographically separated energy plants within the same project calculation. energyPRO is one of the world's most advanced and flexible modelling softwares for the design, simulation, optimization and detailed technical and financial planning of energy projects. In addition, energyPRO accounts for all system costs along with SO_2 and NO_X penalties. energyPRO has been used in modelled single-projects where 100% of the demand was supplied by renewable resources (Connolly et al. 2010).

Some projects carried out using energyPRO include:

- Optimal designs of small CHP plants in a market with fluctuating electricity prices (Lund & Andersen 2005)
- Models of grid losses and the geographic distribution of electricity generation (Østergaard 2005)
- Optimal operation strategies of compressed air energy storage (CAES) on electricity spot markets with fluctuating prices (Lund et al. 2009)
- Transmission-grid requirements with scattered and fluctuating renewable electricity-sources (Alberg Østergaard)
- Models of energy systems with a high percentage of CHP and wind power (Lund & Münster 2003)

E5. EnergyPLAN

The EnergyPLAN model was developed by the Sustainable Energy Planning Research group at Aalborg University (Aalborg university). It focuses on energy planning in relation to technology, geography, economic and institutional conditions. Approximately ten versions of EnergyPLAN have been created and it has been downloaded by more than 1,200 people (Connolly et al. 2010). The software can be downloaded free of charge simply by filling in a form on the homepage. The training period required can take from a few days to a month, depending on the level of complexity required.

The main purpose of the model is to assist in the design of national or regional energy planning strategies based on technical and economic analyses of the consequences of implementing different energy systems and investments. The model encompasses the whole national or regional energy system and includes heat and electricity supplies outside of the transport and industrial sectors. Several characteristics of EnergyPLAN make it unique when compared to other similar tools. It is a deterministic input/output tool, with the general inputs being demands, renewable energy sources, energy station capacities, costs and a number of different regulation strategies for import/export and excess electricity production. Outputs are energy balances and resulting anual productions, fuel consumption, import/export of electricity and total costs—including income from the exchange of electricity. Any procedures that would increase the calculation time have been avoided in the programming, and the computation of 1 year requires only a few seconds on a normal computer. EnergyPLAN optimises the operation of a given system, rather than optimising investments in the system.

The EnergyPLAN model has been used and applied to various practical cases and research projects. Examples are:

- 100% Renewable energy systems, climate mitigation and economic growth (Mathiesen et al.)
- The first step towards a 100% renewable energy-system for Ireland (Connolly et al.)
- Two energy system analysis models: A comparison of methodologies and results (Lund et al. 2007)
- Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply (Lund 2006)
- Modelling of energy systems with a high percentage of CHP and wind power (Lund & Münster 2003)
- Reviewing optimisation criteria for energy system analyses of renewable energy integration (Østergaard 2009)

- Energy system analysis of 100% renewable energy systems— looking at Denmark in the years 2030 and 2050 (Lund & Mathiesen 2009)

In addition, EnergyPLAN has been used in a number of publications, including PhD dissertations, development projects, peer reviewed journal papers and a number of publications that can be found on the EnergyPLAN website (Aalborg university).

E6 .In*vert*

In*vert* is comprehensive, dynamic, bottom-up simulation tool that was developed by the Energy Economics Group (EEG) at Vienna University of Technology in 2003. New features are regularly added as necessary and the software can be downloaded for free from the homepage (Vienna University of Technology). In*vert* is used to evaluate the effects of different promotional schemes such as investment subsidies, feed-in tariffs and tax exemptions, as well as subsidies on fuel input, CO_2 taxes and soft loans, additional aside premiums on the energy carrier mix, CO_2 reductions and the costs to society of certain strategies. In*vert* simulates different scenarios (price scenarios, insulation scenarios, different consumer behaviours, etc.) and the potential impact of these on future trends in renewable and conventional energy sources. It has more than 170 users and a person can learn to use the software in approximately one day (Connolly et al. 2010).

In*vert* is primarily used to simulate national energy-systems. The simulation can be run for up to a 25-year period using one-year time-steps, and it accounts for all sectors of the energy-system. All thermal and renewable generation except nuclear, wave and tidal can be modelled. However, no storage/conversion technologies are simulated and only bio-fuel transportation is simulated (Connolly et al. 2010). In*vert* focuses specifically on the heat sector by analysing the utilisation of heat pumps, solar thermal, conventional heating systems, etc. Outputs include costs, unit productions, fuel consumption, mix of energy carriers, energy demands and the installed capacities of units required.

In*vert* has been used previously to identify sustainable energy solutions for the town of Jordanów in Poland, the city of Vienna in Austria, the regions of Baden Württemberg in Germany and Cornwall in the United Kingdom, the island of Crete in Greece, and the entire country of Denmark (Connolly et al. 2010).

Some peer reviewed papers where In*vert* has been used for analysis include:

- Policy strategies and paths to promote sustainable energy systems—the dynamic In*vert* simulation tool (Stadler et al. 2007)
- Deriving efficient policy portfolios promoting sustainable energy systems—case studies applying Invert simulation tool (Kranzl et al. 2006)

E7. MARKAL/TIMES

MARKAL is a widely applied, bottom-up, dynamic model that was developed by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA) (Seebregts et al.). MARKAL takes both the supply and demand sides of the energy system into account and provides policy makers and planners in the public and private sectors with extensive detail on energy producing and consuming technologies. In doing this, it provides an understanding of the interplay between the macro-economy and energy. The source code is distributed free-of-charge by signing a Letter of Agreement. The code itself is written in GAMS, which is a commercial language and therefore has to be purchased (Connolly et al. 2010). Months of training are necessary in order to be able to handle the tool. MARKAL/TIMES is a general purpose model where the input data represent evolution over long periods (up to 100 years) of specific energy–environment systems at a global, multi-regional, national, state/province, or community level. All thermal, renewable, storage/conversion and transportation technologies can be simulated by MARKAL/TIMES. Also, many different energy networks or reference energy-systems are feasible for each time period simulated. Therefore, MARKAL/TIMES finds the ‘best’ reference energy-system for each time period by selecting the set of options that minimises the total discounted system cost or the total discounted surplus over the entire planning horizon. The MARKAL/TIMES tools have been used in numerous studies, simulating the evolution of things such as European Commission’s integrated policies on the use of renewable sources, climate change mitigation and energy efficiency improvement. Some of the publications using the tool for the analysis of renewable resources include:

- Renewable energy for sustainable electrical energy system in India (Mallah & Bansal 2010)
- Evaluation of green-certificates policies using the MARKAL-MACRO-Italy model (Contaldi et al. 2007)
- Perspectives on global energy futures: simulations with the TIME model (de Vries et al. 1999)

Appendix F: Introduction to the Maldive Islands

F1: Introduction

This section will give a background to the Maldives by providing a brief introduction to the geographical, physical, social and built environment of the Maldives and the survey carried out. This will provide context, highlighting the island's vulnerability to climate change and the energy situation with regards to power generation. The selected island "Fenfushi" in the Maldives is a suitable case study because of its population size and geography, which represent more than two thirds of the nearly two hundred inhabited islands. These islands are suitable candidates for energy projects like this; their environments support the search for proper sources for electricity mix in generation, given the constraints to conventional diesel generation both in terms of supply shortages and emissions that exist on them. The methodology set out in this thesis could be used in future developments of renewable energy designed to foster greater resiliency during unforeseen events such as the 9/11 incident and in the face of instability in the Gulf and possible wars. One island is studied; this is because these islands are separated by sea and the method is designed to investigate one complete regional energy system. Many environmental factors are of particular importance to these islands, as their unique eco-systems and bio-diversity are highly sensitive to environmental encroachment (Read & University. United Nations 2001). Global warming and the rising sea-level will affect the islands long-term habitability.

F2: Geography

The Republic of Maldives is an island nation in the Indian Ocean. It is composed of a double chain of twenty-six natural atolls stretching in a north-south direction 440 km off India’s Lakshadweep islands, between Minicoy Island and the Chagos Archipelago. The southern atoll of the Maldives is 450 km north of the Chagos Archipelago in the Indian Ocean. It stands in the Laccadive Sea, about seven hundred kilometres south-west of Sri Lanka. Most atolls consist of a large, ring-shaped coral reef that supports numerous small islands. Most of these islands are less than 2 km^2 in land area. They are coral islands with no significant topographic features, with an average elevation of approximately 2 metres above mean sea level. The islands are typically formed on the rim of an atoll enclosing a central lagoon. The Maldives is one of the smallest sovereign states in the world in terms of land area, with an estimated 235km^2 of land, divided over 1190 islands (Bray 1998; Jameel 2007; MPND 2007). It stretches 900km across the Indian Ocean, from latitude 7°6' 35"N crossing the Equator to 00º 42'24"S and longitude of 72º 33' 19"E to 73º 46'13"E (Ministry of Planning and National Development 2007). Its nearest neighbours are India, Sri Lanka and the Chagos Islands. The width of the chain varies from 80 km to 130 km. The Exclusive Economic Zone (EEZ) of the Maldives is around 1,000, 000 km^2 of maritime area (Fürst 1999)—according to the government statistics it is 859,000 km^2 (MPND 2007). Figure F.1 shows the geographic location of the Maldives, its neighbouring countries and how it stretches from North to South forming two chains of natural atolls. The 26 natural atolls have been divided into roughly 20 divisions for administrative purposes—these divisions have changed slightly over the years according to the Government’s policies.

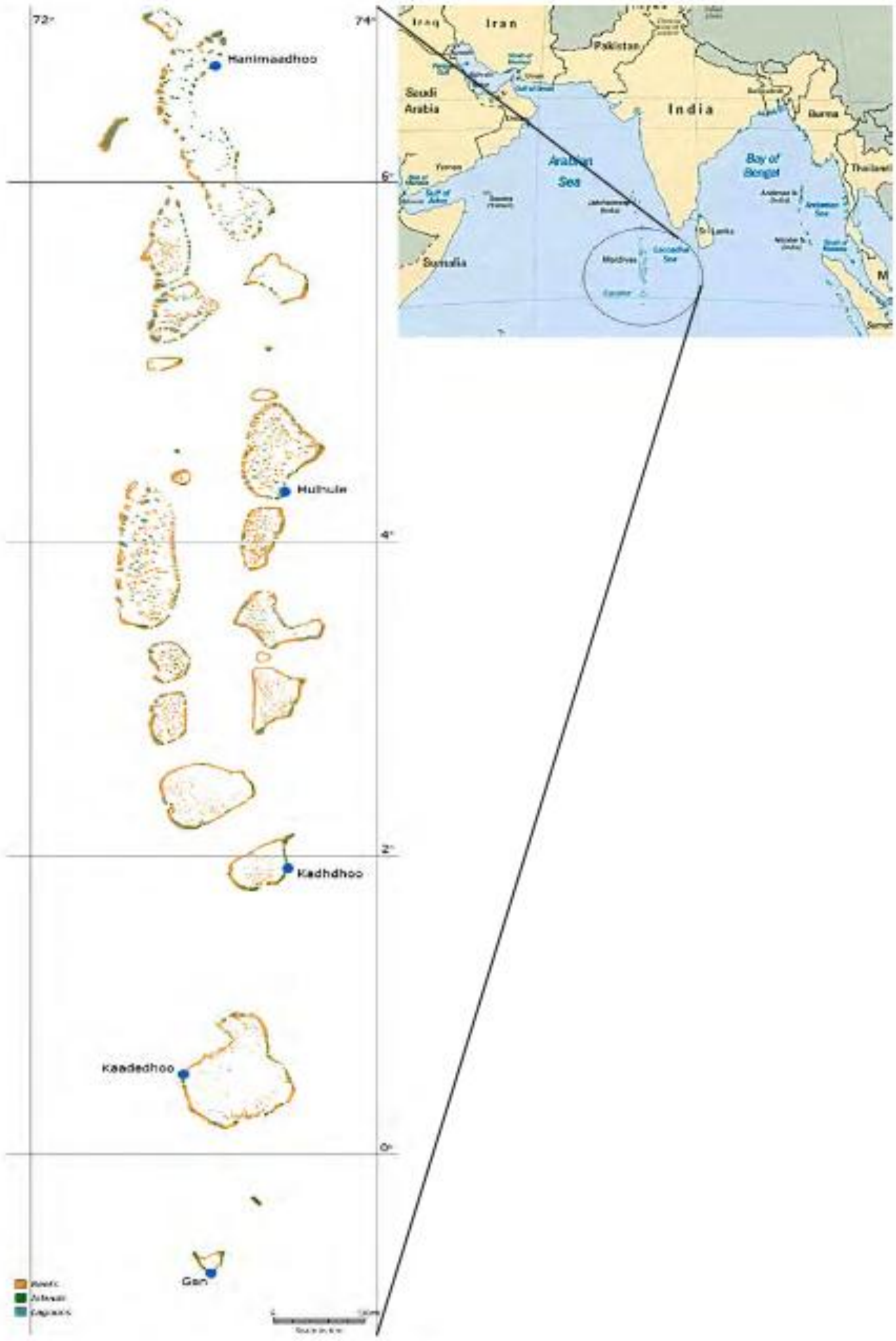


Figure F.1 Map of the Maldives showing its natural atolls and local weather observation stations marked with small blue dots

F3: Climate

The Maldives has a warm and humid tropical climate that is described as monsoonal. The weather is dominated by two monsoon periods—a wet season known as the southwest monsoon and a dry season known as the northeast monsoon. The southwest monsoon lasts from May to September, with October and November acting as a transition period between the southwest and northeast monsoons. The northeast monsoon is from December to February with March and April acting as the transition period between the two monsoons. The wetter southwest monsoon is typically the period when most severe weather events occur. The Maldives is not located in a region prone to cyclones or other intense climatic events but, according to Jameel, there has been historic evidence that the northern part of the Maldives was affected by storms generated from cyclone activities (Jameel 2007). All weather data presented in this thesis are derived from the five local weather stations marked in Figure F.1, all of which were established at different times. Table F.1 is a summary of the monsoon periods in the Maldives.

Table F.1 Summary of the monsoon periods experienced in the Maldives

Monsoons/transitions	**Months**
Northeast monsoon	December, January and February
Transition from northeast to southwest monsoon	March and April
Southwest monsoon	May, June, July, August, September
Transition from southwest to northeast monsoon	October and November

As the Maldives lies close to the equator, there are no significant annual variations in temperature, although marked seasonal variation in wind speed and rainfall is observed. The Maldives experiences two peaks in rainfall, one during the southwest monsoon and one during the northeast monsoon. The reason for this is the country’s close proximity to the equator and the fact that the Inter-tropical convergence Zone (ITCZ) crosses the Maldives twice in a year. This occurs around April-May, while the ITCZ is moving towards Asia, and again during September–October, when the ITCZ is retreating back to the Southern hemisphere. Figure F.2 shows the location of the ITCZ during the Northern Hemisphere summer and winter, respectively. Figure F.3 shows the monthly hours of sunshine for the year 2006 for the north, central and south Maldives and Figure F.4 shows the monthly number of sunshine hours for the central Maldives from 2006-2008.

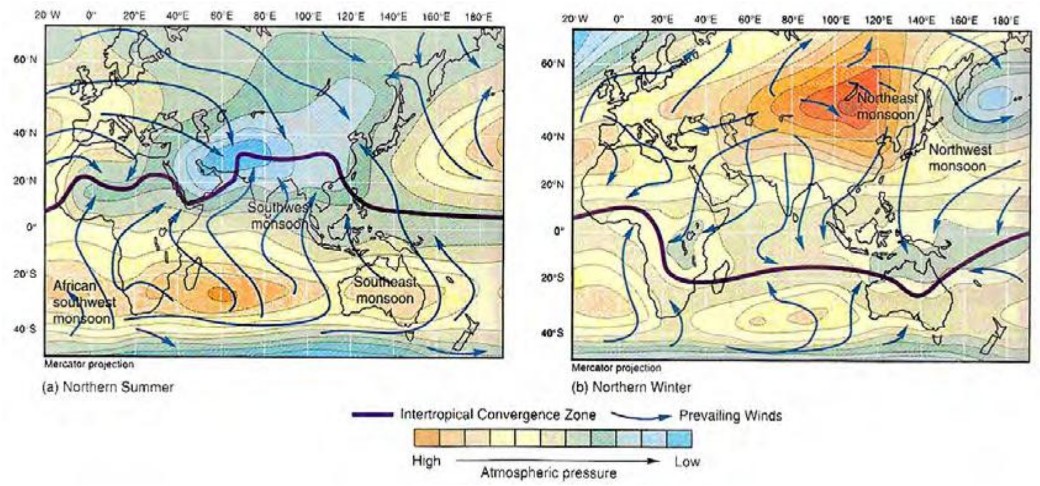


Figure F. 2 Location of the ITCZ by the dark thick line, with the general wind direction during the Northern Hemisphere summer and winter indicated by arrows (adapted from (Segar 1998; Shareef 2009))

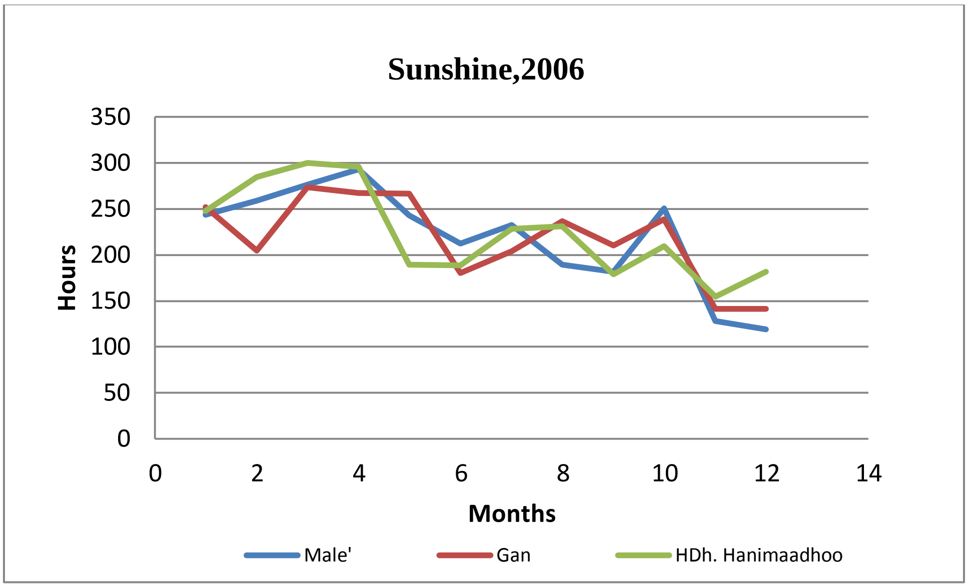


Figure F. 3 Duration of sunshine for three different locations in the Maldives

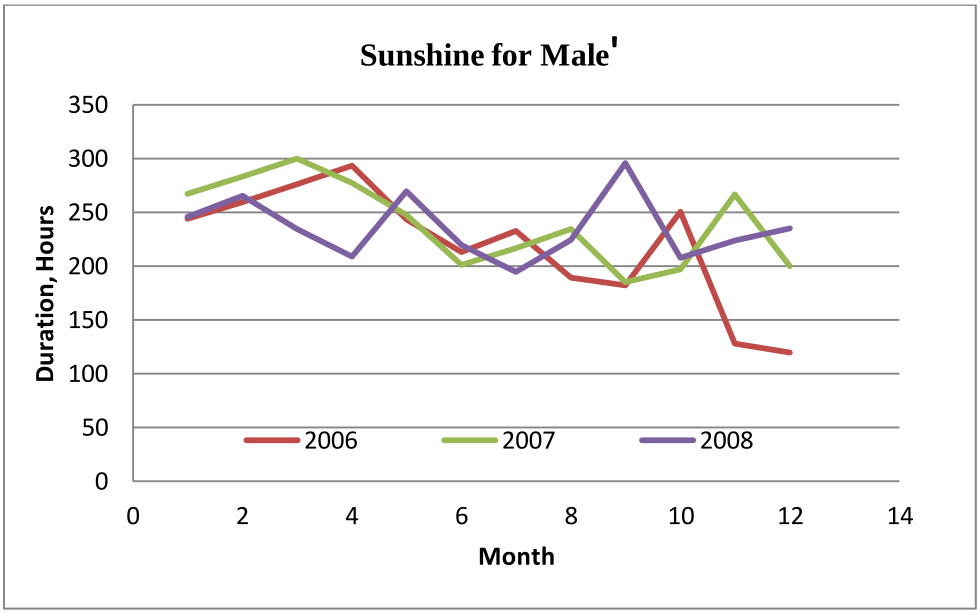


Figure F. 4 Duration of sunshine for the central part of the Maldives

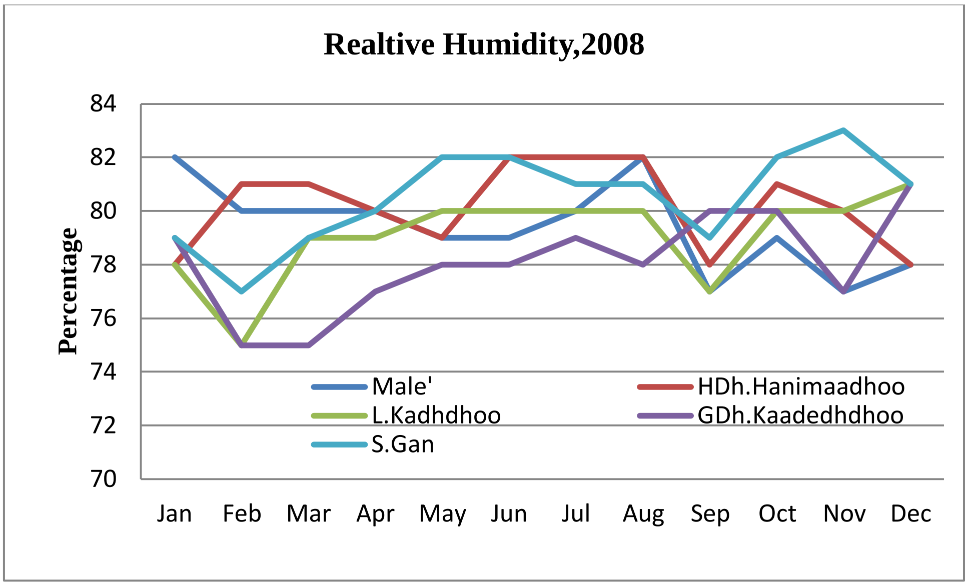


Figure F.5 Relative humidity in percentage

The Maldives is a humid country where the relative humidity ranges from 73 to 85%. Figure F.5 shows the relative humidity in percentages for the year 2008 based on data from the five weather stations. There were no significant changes in relative humidity over the past five years.

F3.1: Climate Trends

The following section gives trends in the general climate of the Maldives.

F3.2: Temperature Variations

Throughout the year, temperature remains fairly consistent in the Maldives. However, daily temperature varies from around 31 degrees Celsius during the day to 23 degrees Celsius at night. The mean daily maximum temperature for central parts of the Maldives was 30.9 degrees Celsius in 2008 and the mean minimum temperature was 26.1 degrees Celsius in the same year. Table F.2 shows mean daily maximum and minimum temperatures for north, south and central parts of the Maldives for the year 2008.

Table F. 2 Mean daily maximum and minimum temperatures, 2008

Location	Mean daily Max. °C	Mean daily Min. °C
North (HDh.Hanimaadho)	30.9	25.1
Central (Male')	30.9	26.1
South (S.Gan)	30.6	25.0

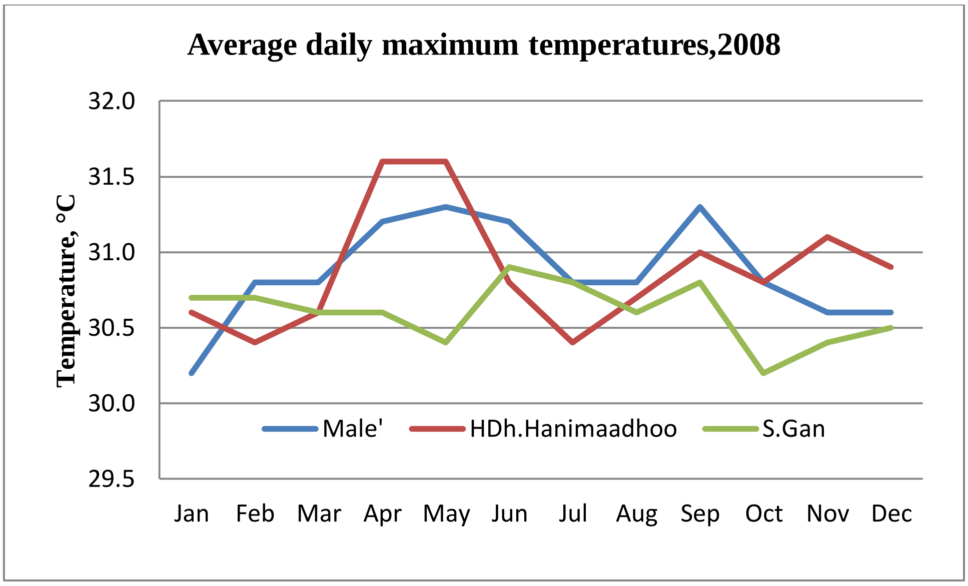


Figure F.6 Average daily maximum temperatures, by month, 2008

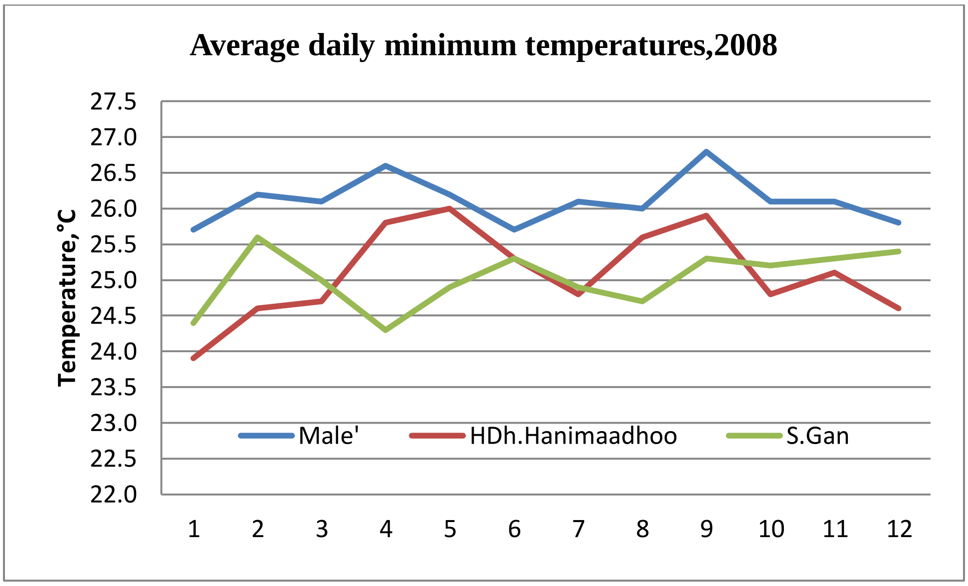


Figure F.7 Average daily minimum temperatures, by month, 2008

Daily temperatures vary little throughout the year with a mean annual temperature of around 28 °C. An analysis of temperature variations from 1974 to 2004 by Jameel shows a long-term annual maximum temperature increase of 0.17 °C every 10 years, whilst annual minimum temperatures show an increase of 0.07 °C every 10 years (Jameel 2007). Figure F.6 and Figure F.7 shows the average daily maximum and minimum temperatures by month for the year 2008 throughout the country.

F3.3: Rainfall

In the wet season (the southwest monsoon) the Maldives experiences torrential rain. Normally rainfall in the Maldives varies between the northern atolls and the southern atolls with the amount of rainfall increasing towards the south. This difference in rainfall patterns is primarily due to the northeast monsoon period and April being much drier in the north than in the south (Edwards 1989) but in recent years the pattern has been changing, as seen from Figures F.10, F.11 and F.12.

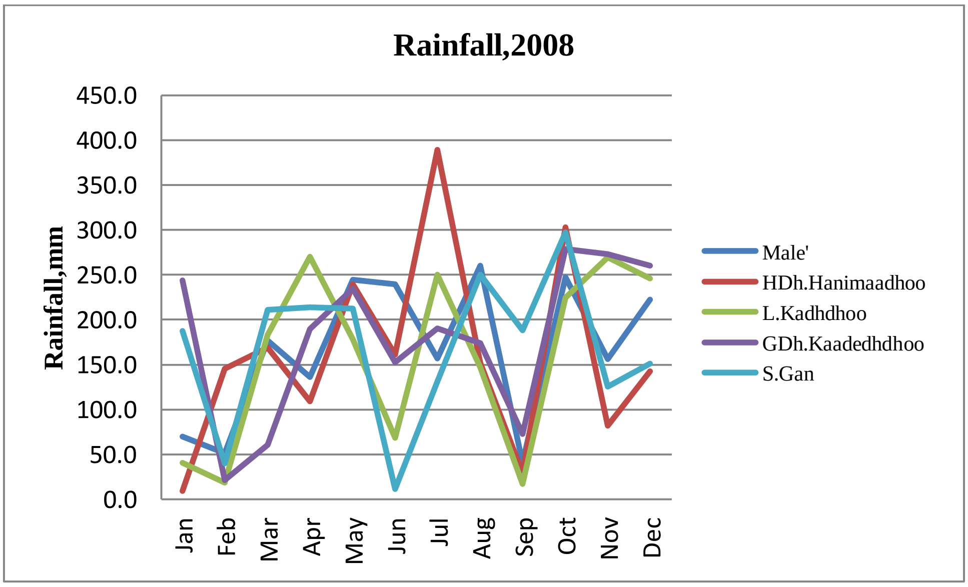


Figure F.10 Monthly rainfall records from five weather stations, 2008

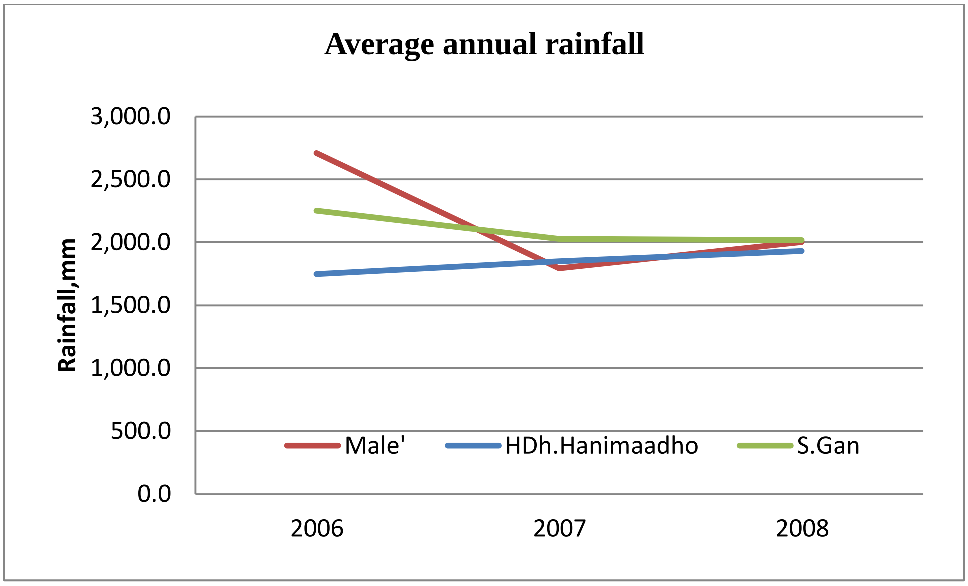


Figure F.11 Average annual rainfall for the north, central and south areas of the Maldives for 2006, 2007 and 2008

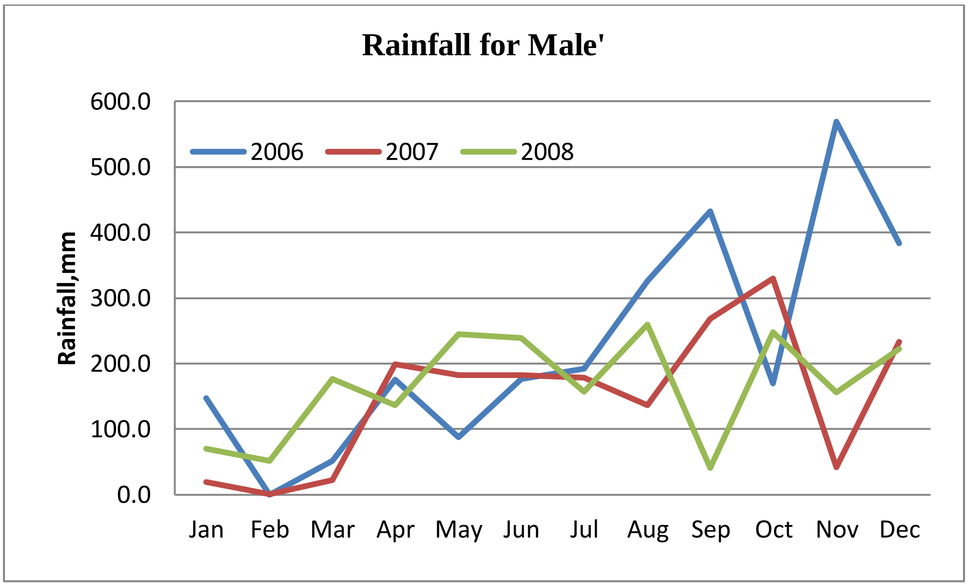


Figure F. 12 Monthly rainfalls for the central part of the Maldives in 2006, 2007 and 2008

A long-term analysis of total annual rainfall data for the central part of the Maldives shows a decrease of 2.7 mm in rainfall every year (Jameel 2007).

F3.4: Wind

In the Maldives the dominant wind directions are west, northwest, northeast and east-northeast. Figure F.15 shows the five year (2003-2007) average wind frequency and direction for the central part of the Maldives. Winds associated with the southwest monsoon are stronger than the northeast monsoon and normally come from the west. On average, wind speeds vary between 2.68-6.26 metres per second (6-14 miles per hour, MPH). The stormiest months are typically May, June and July during the early part of the southwest monsoon. Storms and squalls producing wind gusts of 50-60 knots have been recorded on Male' (Jameel 2007). Figure F.13 shows the variation in average seasonal wind speeds for the central part of the Maldives in miles per hour between 2006-2008. Figure F.14 shows the five year monthly daily maximum, daily high, mean, daily low and daily minimum wind speeds for the central region of the country in meters per second along with the average five year annual values.

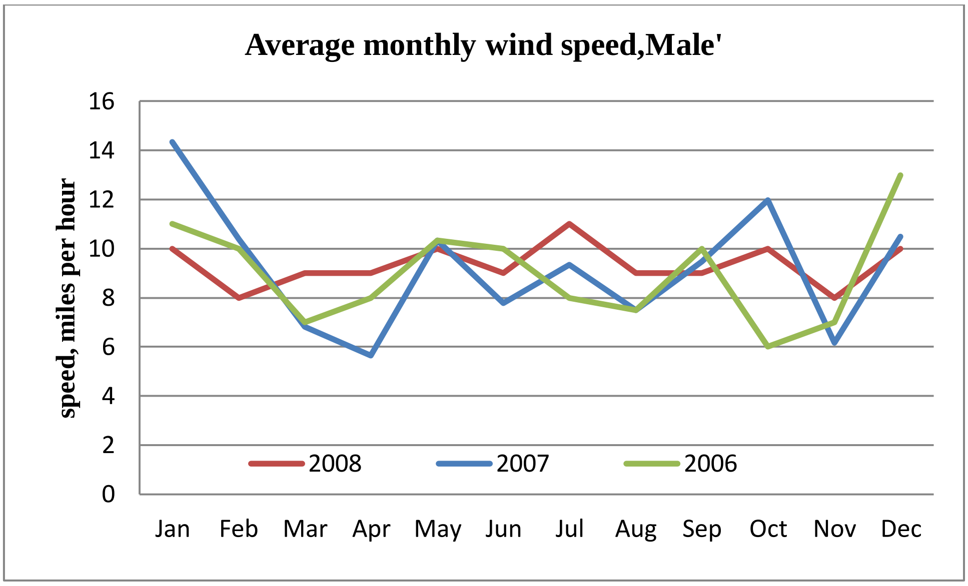


Figure F.13 Average monthly wind speed for the central part of the Maldives

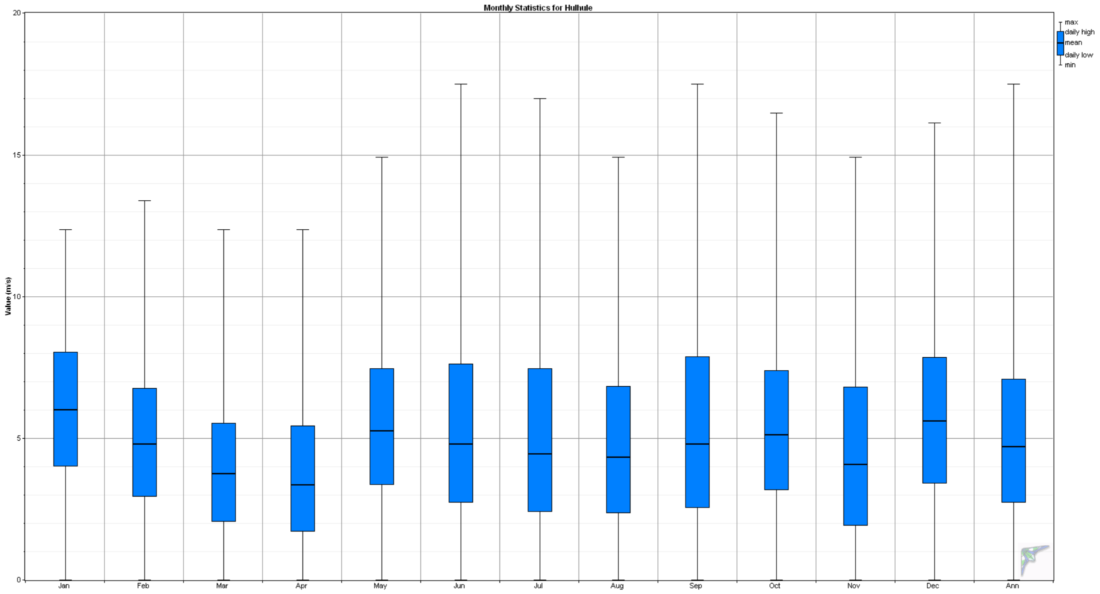


Figure F.14 Monthly wind speeds for the central part of the Maldives from 2003-2007

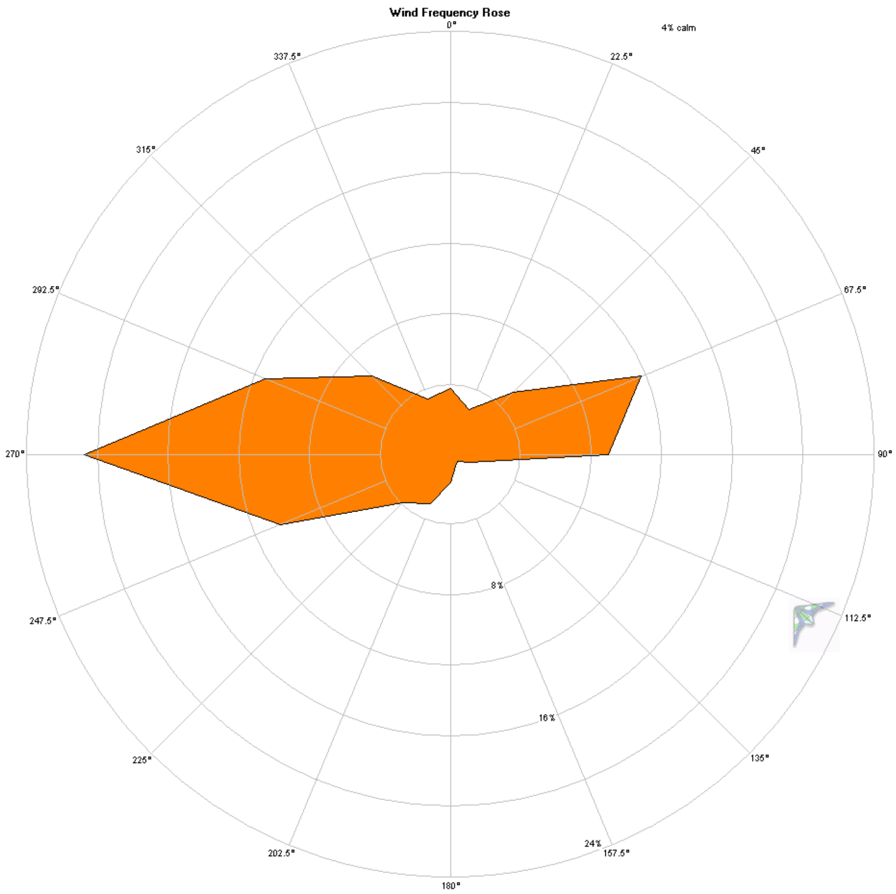


Figure F.15 Wind frequency and direction for the central part of the Maldives (source data: Department of Meteorology, Maldives)

F3.5: Sea Level Rise

Sea level rise is one of the greatest threats posed to the mere existence of these low lying islands. In the past two or three decades there has been increased number of severe cases of soil and beach erosions reported. By 2009 the number of inhabited islands reporting severe erosion had reached 164 (MPND 2009). Recorded data from 1989 to 2005 at Hulhule' weather station (central weather station) shows an increase of 1.7 mm/year. Figure F.16 shows the data gathered from long-term observation and the increasing sea level. According Hay (Hay 2006) the rise in relative sea-level observed in the Maldives is consistent with global observations over the last 100 years, with the rate potentially accelerating due to global warming.

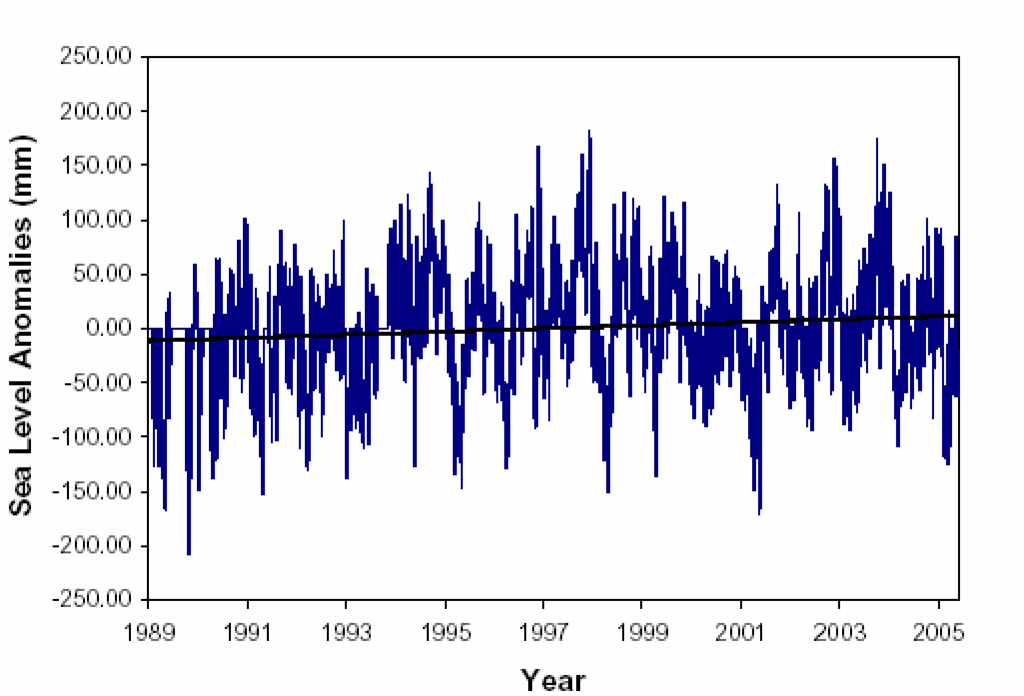


Figure F.16 Daily mean values of sea level for Hulhule' relative to mean sea level (source: (Hay 2006))

F4: Water Resources

The hydrology of the Maldives is typical of coral islands. These islands have very little fresh water resources and due to their scattered pattern, more than 99 % of the country is sea. Water is one of the Maldives' most scarce and precious resources. Figure F.17 shows the water lens of a typical coral island. The main water resource of the Maldives is the fresh groundwater that is found in the porous coral sediments on many of the islands. The domestic water supply of the Maldives is mainly based on rainwater, well water and desalinated water. Rainwater and well water are the dominant sources of water in the atolls. The fresh water lens on Male' has been depleted due to the high density of population and thus the high usage of ground water. As a result a lot of desalinated water is used on Male', all of which is provided by the Maldives Water and Sewerage Company (MWSC).

According to government statistics, less than 25 % of the population used ground water for drinking and cooking during 2006, although traditionally Maldivians have been dependent on groundwater from shallow wells dug in the ground for most of their daily needs. The quality of groundwater is very much influenced by seasonal changes and each individual island's location. The same study claimed that "The fresh groundwater is found as a freshwater lens that comprises a freshwater zone underlain by a transition zone of a few meters thickness between the freshwater and underlying seawater. The top of each freshwater lens found in the islands of Maldives is generally 1.5 to 2 m below the land surface and changes continuously with the tide".

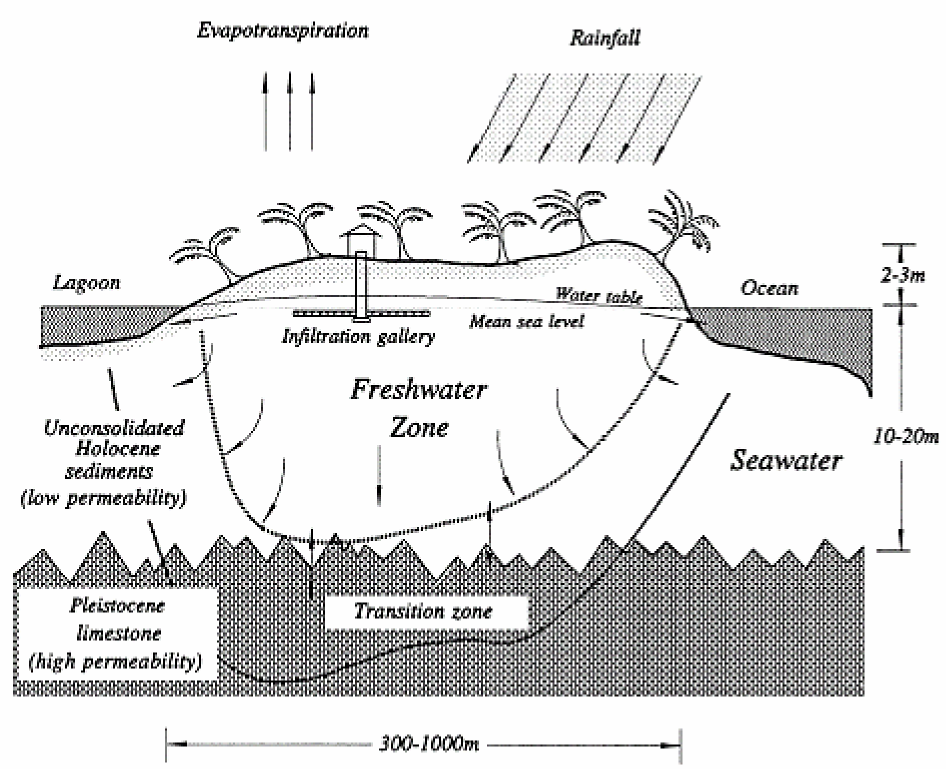


Figure F.17 Cross-section of an island showing features of groundwater (source: (Falkland 1993))

Maldivians have traditionally depended on shallow ground wells for their drinking and cooking water. However, fifteen years ago every household in Male' was given access to desalinated water and almost every household on the remote islands is sustained by synthetic water tanks with either 5000 or 10,000 litres capacity. As a result, most of the people on the islands now use rain water for drinking as well, except during prolonged periods without rain. Rainwater is harvested by individual households from their roof during rain showers and some islands have public storage tanks. Before the harvesting of rainwater begins, the roofs and storage vessels are cleaned by the initial burst of rain.

After the 2004 Indian Ocean Tsunami the ground water on many islands became unusable and, according to Jameel, still had not recovered three years later. Following the tsunami, during dry periods many islands across the country are supplied with desalinated water. Though the ground water on these islands is not very high in salinity, studies have found high levels of bacterial contamination. The main source of contamination is discharge and leakage from septic tanks. Even though every household in Male' is supplied with desalinated water, rainwater is still harvested by some households during the rainy season. Around 3% of the households in Male'use rain water for cooking and drinking where as on the atolls the figure is 76% (MPND 2009).

F5: Population

According to the 2006 census the population of the Maldives was 298,968. The population passed the 300,000 mark in July 2006 (MPND 2009). Figure F.18 shows the population of Maldives from 1911-2006. The annual population growth rate has declined significantly, going from 3.43% in 1985-1990 censuses to 1.69% in the 2000-2006 census. At the current rate of growth, the population would double in 40 years. The populations on the atolls and the islands differ across the country. More than a third of the total population lives in the capital Male'. Among the atolls, Addu Atoll (the southern-most atoll) has the highest population at 18,028 and Vaavu Atoll has the lowest population at 1,606 (MPND 2009).

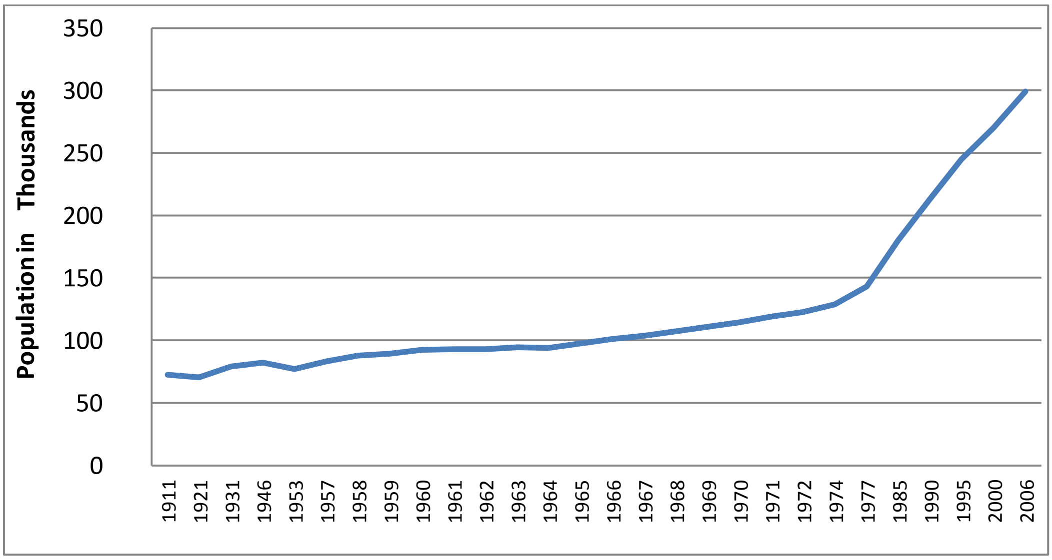


Figure F.18 Population of the Maldives from 1911 to 2006 (source data: (MPND 2009))

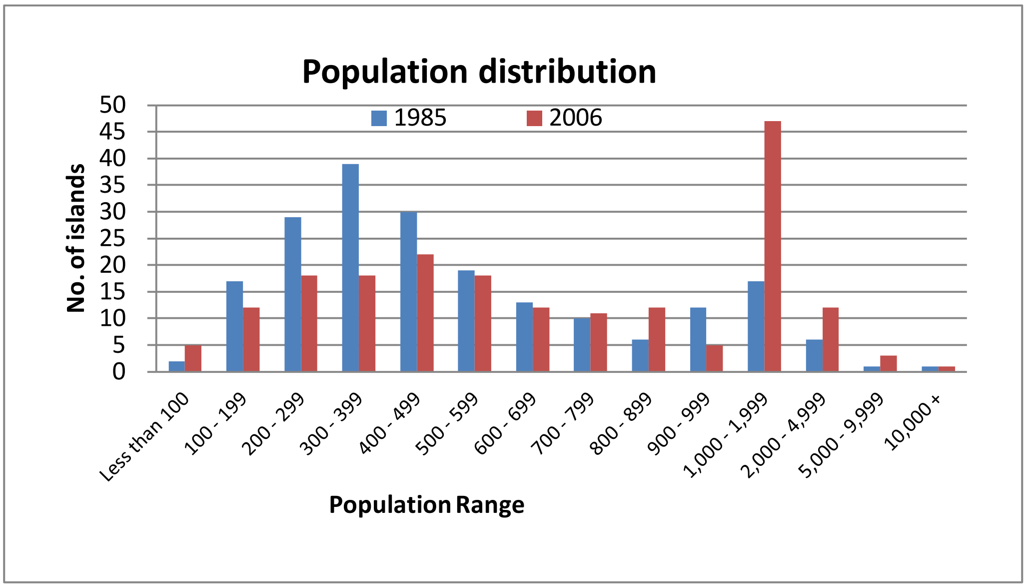


Figure F.19 Population distribution of islands

The population distribution of the islands is given in Figure F.19. Only three islands have a population greater than 5000 other than Male', which has a population of over one hundred thousand. In 2006, 57 islands had a population of between 1000 and 5000 people, 60 islands had a population of between 500 and 1000 people and 74 islands had a population of less than 500 people.

F6: Daily Life on the Islands

This section briefly discusses what the daily life on the Maldivian islands looks like. The day to day activities of the people on the different islands vary according to their location and the island's traditional occupations. On islands closer to good fishing grounds men normally go fishing and the majority of men from islands closer to tourist resorts are employed in resorts.

F6.1: On Fenfushi Island

Since the field work was carried out on Fenfushi, the daily life of people on Fenfushi will be discussed in detail. Most people wake up very early in the morning, usually before sunrise. Most men go to work at the nearby resort islands. Only a few people are employed by governmental institutions such as the island office, the judicial court, the health centre and the school. Some women go to nearby resort islands to work as cleaners (mainly sweeping); the women who remain on the island take part in activities such as weaving mats from coconut leaves, making ropes from coconut husk fibre and preparing local food items for local resort staff. A number of families from this island live in Male’ because of the better job opportunities, education and medical treatment available. Some of the residents are self-employed, working as carpenters, builders (of houses) and shop owners and some people engage in odd jobs, helping out on boat building sites and cooking.

F7: Education

Like most of the remote Maldivian islands, Fenfushi School goes up to grade 10; there were about two hundred students enrolled in 2008. Only a few islands teach up to grade 12 in the Maldives. In Male’ there are a number of schools that teach up to grade 12—also sometimes called GCSE (General Certificate of Secondary Education) Advanced levels. The Maldives College of Higher Education and some other colleges provide courses in different disciplines to undergraduate level, as well as some masters level programmes.

F8: Living Situation

Most of the houses on Fenfushi are built from concrete (cement) and have corrugated iron roofs. Most have three bedrooms, one sitting room and two bathrooms with showers and toilets—these are often attached to bedrooms. Most households have their kitchen in a separate building. Most of the cooking is done by LPG (Liquefied Petroleum Gas) stoves with two ports, though almost every household has facilities for cooking with firewood. Traditional houses built from plant material have all been replaced with homes made out of concrete and iron: these modern houses are hot and uncomfortable without ceiling fans. A previous study by Hamm (Hamm 2007) showed that the inside temperature of concrete houses is two degrees higher than thatched houses. In the 1970s traditional thatched houses started being replaced by houses built from coral from the reef; now modern houses are built from cinder cement blocks because coral mining has been banned in most of the parts in the country.

Figure F.20 Coral used for construction of buildings

Traditionally all village homes, businesses and municipal buildings are constructed out of coral (Figure F.20). Many village homes are now a mixture of traditional coral and the newer cinder block construction (Sluka & Miller 1998). Figure F.21 shows a house made of cinder blocks.

Figure F.21 Cinder block construction

F9: Transportation System

There are two parts to this section—transport to and from the islands and transport on the island.

F9.1: Transport To and From the Island

A variety of transport options are available in the Maldives. There are five airports that offer domestic flights and operate a regular schedule. These airports have weather stations. Sea planes operate on most resort islands. The most widely used mode of transport between the local islands is mechanised boats. The size of the boats varies from 30 feet to 100 feet.

F9.2: Transport on the Island

Most of the remote islands have few vehicles. Fenfushi at the time the field work for this research took place had 1 ambulance, 1 pickup, 3 motor bikes (scooters), 2 hand carts and 22 bicycles. There are no paved roads and passenger vehicles are not an essential, as the island is less than a kilometre in length. But on Male' there are hundreds of motor vehicles and there are a few other islands with significant numbers of motor vehicles.

Appendix G: Wind Analysis

G1: Global Wind Patterns and Wind Data

In order to understand the local weather and wind patterns, general global phenomena need to be understood first. In this section a broader global wind pattern will be discussed. The region of the Earth receiving the Sun's direct rays is the equator. Here, air is heated and rises, leaving low pressure areas behind. Moving to about thirty degrees north and south of the equator, the warm air from the equator begins to cool and sink. Between thirty degrees latitude and the equator, most of the cooling sinking air moves back to the equator. The rest of the air flows toward the poles. The air movements toward the equator are called "trade winds"—warm, steady breezes that blow almost continuously. The Coriolis Effect makes the trade winds appear to be curving to the west, whether they are travelling to the equator from the south or north (Choudhuri & Gilman 1987; Lackner & Dizio 1994). The trade winds coming from the south and the north meet near the equator. These converging trade winds produce general upward winds as they are heated, so there are no steady surface winds. This area of calm is called the doldrums. Between thirty and sixty degrees latitude, the winds that move toward the poles appear to curve to the east. Because winds are named from the direction in which they originate, these winds are called prevailing westerlies. At about sixty degrees latitude in both hemispheres, the prevailing westerlies join with polar easterlies to reduce upward motion. The polar easterlies form when the atmosphere over the poles cools. This cool air then sinks and spreads over the surface. As the air flows away from the poles, it is turned to the west by the Coriolis Effect. Again, because these winds begin in the east, they are called easterlies. Figure G.1 shows the circulating pattern by three major cells—the Hadley Cell, the Ferrel Cell and the Polar Cell (Forget et al. 1999; Seinfeld & Pandis 1998).

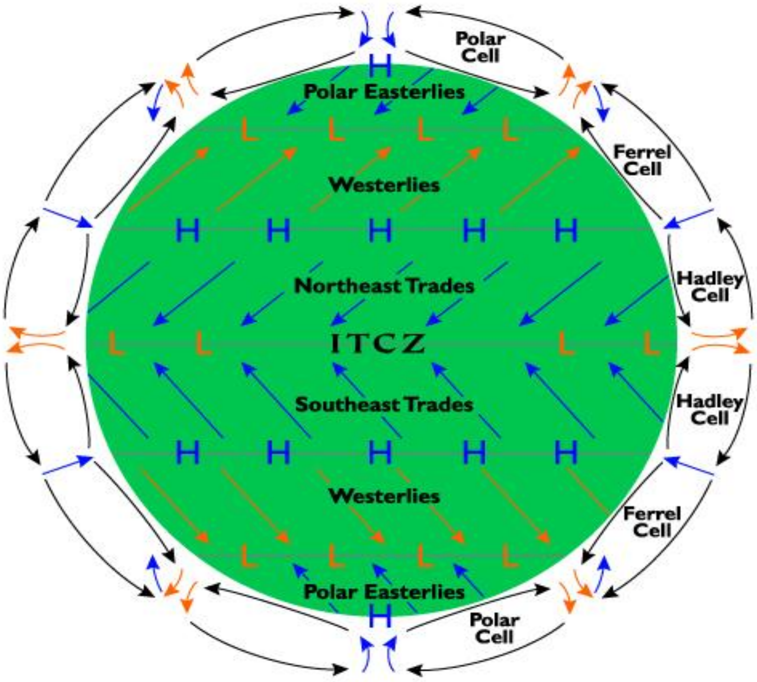


Figure G.1: The Global Wind Systems
(Fromhttp://homepages.ius.edu/PGALVIN/climate/wind_files/Winds.jpg)

What regulates these winds are the three cells mentioned or circular wind patterns in both the northern and southern hemispheres—one near the equator, one at the poles and one in between. The trade winds from both hemispheres converge on the surface at the equator, which sends the air aloft and reduces the pressure. This is why it rains so much around the equator. When the air reaches the upper altitudes, some of it heads north and some heads south in an effort to even out the heat difference between the equator and the poles. At about 30 degrees latitude, the high-altitude winds sink to the surface. Sinking winds create high-pressure zones, with lots of sun, which is why 30 degrees latitude is where the world’s great deserts are. Some of that sinking air heads back to the equator, which keeps this cell or circular wind pattern going. Some of the high winds descend at the poles. From there they head back toward the equator and converge with the prevailing westerlies at 60 degrees. When winds converge, they rise. This results in frequent storms areas at 60 degrees. In general, there is a number of prevailing wind conditions on the surface and at higher altitudes in both hemispheres that greatly affect the weather. Where winds converge on the surface at the equator, the air moves upward resulting in lots of storms and rain. At 30 degrees winds diverge at the surface, high winds move downward and create deserts and dry weather. At 60 degrees latitude, winds converge uplifting with resultant storm activity.

Though surface winds may differ at different latitudes, at above 15,000 feet in the troposphere the wind is generally from the west. This is why big storms move from the west to the east. During the summer the winds can shift in the tropics, which is why hurricanes head east. This complex system, where air moves in complex patterns, stirring up in the process can cause an El Nino effect. Which as known from recent history can have dramatic effects on the climate (Rasmusson & Carpenter 1982; Vecchi & Harrison 2010).

G2: Global Wind Maps

Global wind maps were also used to compare the data obtained from the meteorological department of the Maldives.

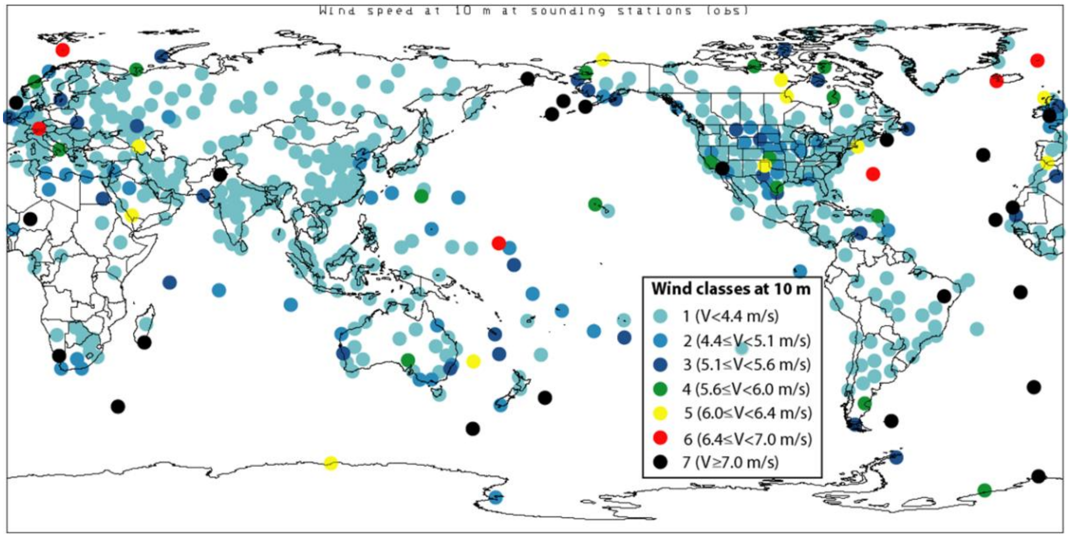


Figure G.2 Global wind map
(http://www.stanford.edu/group/efmh/winds/global_winds.html)

The global wind map shows that the Maldives lies in a 4 to 6 m/s average wind speed zone; the mean wind speed considered here is for 10 meters above ground level. For the power generation input to the wind turbines the five year average wind speeds generated from the central (Hulu'le) weather station was used. The data obtained from the Maldives Meteorological department is considered valid as it does not deviate much from the results of other studies. The Meteorological department is equipped with modern instruments and the staff are trained to make observations.

G3: Wind Speed and Direction

Wind speed at a given point is the simplest representation and is important for most of the analysis. Anemometers are commonly used to measure the wind speed. Wind speeds can be calculated as an average or expressed as an instantaneous value. Wind speed averaging intervals commonly used in resource assessment studies include 1- or 2- minute (weather observations), 10-minute (often used in the wind monitoring programs), hourly, monthly and yearly periods. Measuring the height of the wind speed is important as the speed varies with the height and it is important to know the exposure of a particular location to the prevailing winds—nearby obstacles such as trees and other structures can reduce the wind speed. Wind direction is measured with a wind vane, usually located at the same height as the anemometer. Knowledge of the prevailing wind direction is important in assessing the available resource. Correct alignment of the wind vane to a reference direction is important to accurately measure the wind direction, but they are not always properly aligned. Wind direction observations at meteorological stations are often based on a 36-point compass (every 10 degrees). Some wind direction data are expressed in less precise 8-point (every 45 degrees), 12-point (every 30 degrees), or 16-point (every 22.5 degrees) intervals (Elliott et al. 2003).

The wind direction distribution is often presented as a wind rose; a plot of frequency of occurrence by direction. Wind roses can also represent quantities such as the average speed or the percent of the available power for each direction. The wind at a given location is characterised by the wind speed frequency distribution. Two main factors are how often a given wind speed is observed and the range of wind speeds observed at the location. Locations with identical average wind speeds but with different distributions can result in available wind resources varying as much as a factor of two or three (Elliott et al. 2003).

G4: Weibull Distribution Function

The Weibull distribution (named after W. Weibull, a Swedish physicist) provides a close approximation of the probability laws of many natural phenomena. It has been used to represent wind speed distributions in a number of research and application works for a long time. Weibull distribution fits experimental wind data and is very flexible and simple in its application (Lange 2005; Rehman et al. 1994; Zaharim et al. 2009). The Weibull Function is defined as:

$$f(V) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^{k}}$$

Where:

$f(V)$ = the Weibull probability density function, the probability of encountering a wind speed of V m/s;

c = the Weibull scale factor, which is typically related to the average wind speed through the shape factor, expressed in m/s;

k = the Weibull shape factor, which describes the distribution of the wind speeds.

Detailed explanations of the Weibull Distribution Function and its application are available in many texts, such as by Rohatgi & Nelson and Zaharim & REzali (Celik 2004; Rohatgi & Nelson 1994; Zaharim et al. 2009).

G5: Wind Power Density

Wind power density provides a truer indication of a location's wind energy potential. Wind power density expresses the average wind power over one square meter (W/m^2). The power density is proportional to the sum of the cube of the instantaneous (or short-term average) wind speed and the air density. As a result of this cubic term, two sites with the same average wind speed but different distributions can have very different wind power density values (Elliott et al. 2003). The wind power density (W/m^2) is computed using the following equation:

$$WPD = \frac{1}{2n}\sum_{i=1}^{n}\rho V_i^3$$

Where

WPD = the wind power density in W/m^2;

n = the number of records in the averaging interval;

ρ = the air density (kg/m^3) at a particular observation time;

V_i^3 = the cube of the wind speed (m/s) at the same observation time.

The above equation should only be used for individual measurement records (hourly, 10-minute, etc.) and is not suitable for long-term average records that use monthly or yearly values. This equation will underestimate the wind power density if long term averages are used, because long-term averages do not include most of the higher-speed records that would more accurately calculate the wind power density. The density of air (ρ) is dependent on temperature and pressure and can vary by 10% to 15% seasonally (Elliott et al. 2003). If the site pressure and temperature are known, the air density can be calculated using the following equation:

$$\rho = \frac{P}{RT}$$

Where

ρ = the air density in kg/m^3;

P = the air pressure (Pa or N/m2);

R = the specific gas constant for air (287 J/kg·K);

T = the air temperature in degrees Kelvin (°C+273).

If the pressure is not available, density of air can be estimated as a function of the location's elevation and temperature; detailed formulations are given in many subject oriented texts.

G6: Wind Shear and the Power Law

Wind shear or wind gradient is a difference in horizontal wind speed with height and direction over a relatively short distance in the atmosphere. The magnitude of the wind shear is site-specific and dependent on wind direction, wind speed and atmospheric stability. By determining the wind shear, one can extrapolate existing wind speed or wind power density data to other heights. The following form of the power law equation can be used to make these adjustments:

$$U = U_0 \left(\frac{z}{z_0}\right)^{\alpha}$$

$$WPD = WPD_0 \left(\frac{z}{z_0}\right)^{3\alpha}$$

Where

U = the unknown wind speed at height z above ground;

U_0= the known speed at a reference height z_0;

WPD = the unknown wind power density at height z above ground;

WPD_0 = the known wind power density at a reference height z_0;

α = the power law exponent.

An exponent of 1/7 (or 0.143), which is representative of well-exposed areas with low surface roughness, is often used to extrapolate data to higher heights.

G7: The Potential of Wind Power

The wind potential for electricity generation depends on how good the available wind resource is. For smaller systems with few kilowatts, it is necessary that the wind turbines are sufficiently close to the control house for economic reasons. The economic feasibility of wind power systems depends on the cost of alternative systems to wind. The modelled wind turbines are assumed to be installed at the western spit of the island, which is less than a kilometre from the existing power house.

G8: At Hanimadhoo Weather Station

Figures G.3 to G.6 demonstrate the important findings in graphical form based on the wind analysis of data at Hanimadhoo weather station.

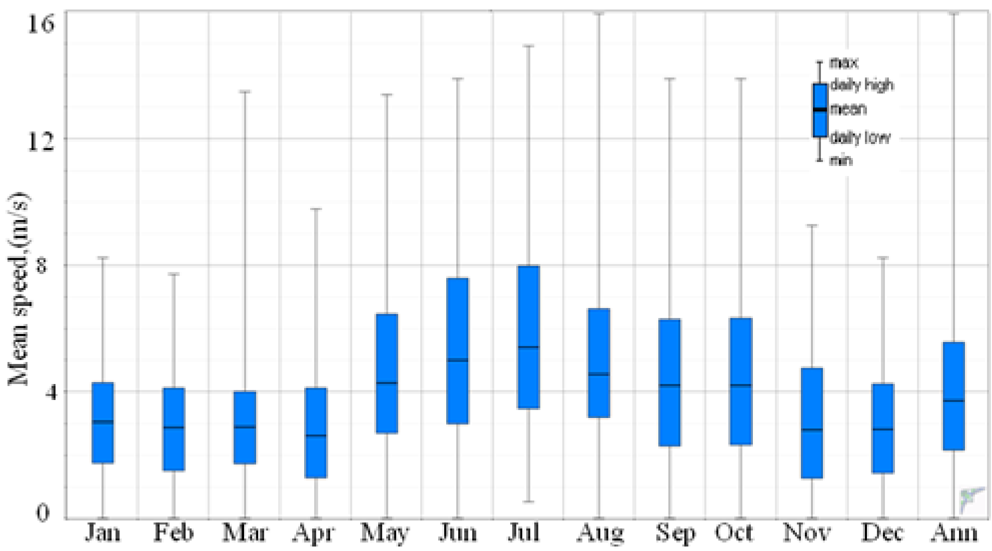


Figure G.3 Monthly mean wind variations at Hanimadhoo from 2003-2007

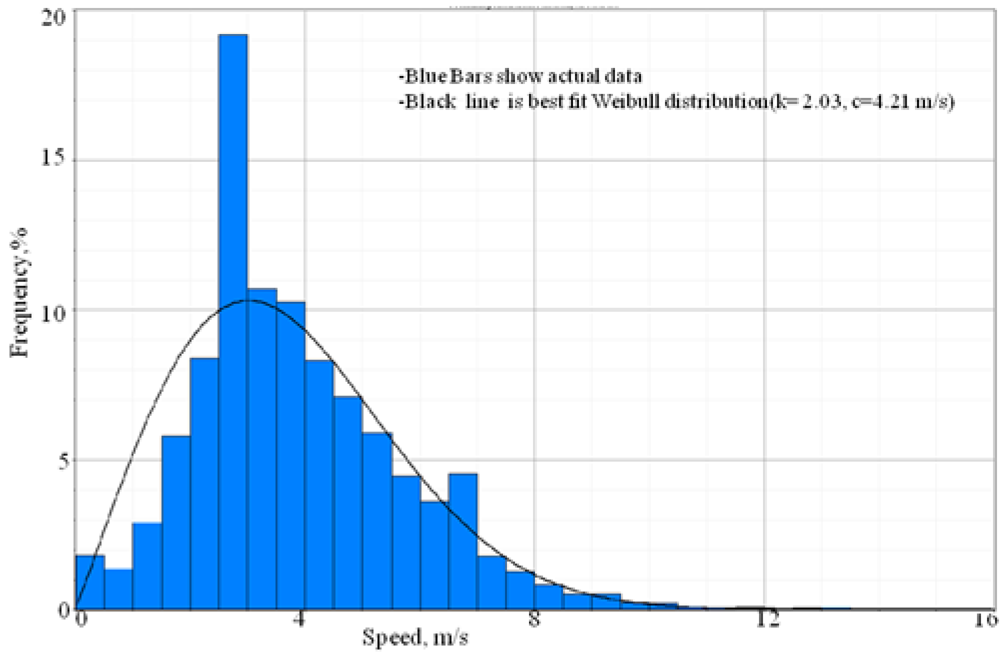


Figure G.4 Probability distribution function of wind speed at Hanimadhoo from 3007-2007

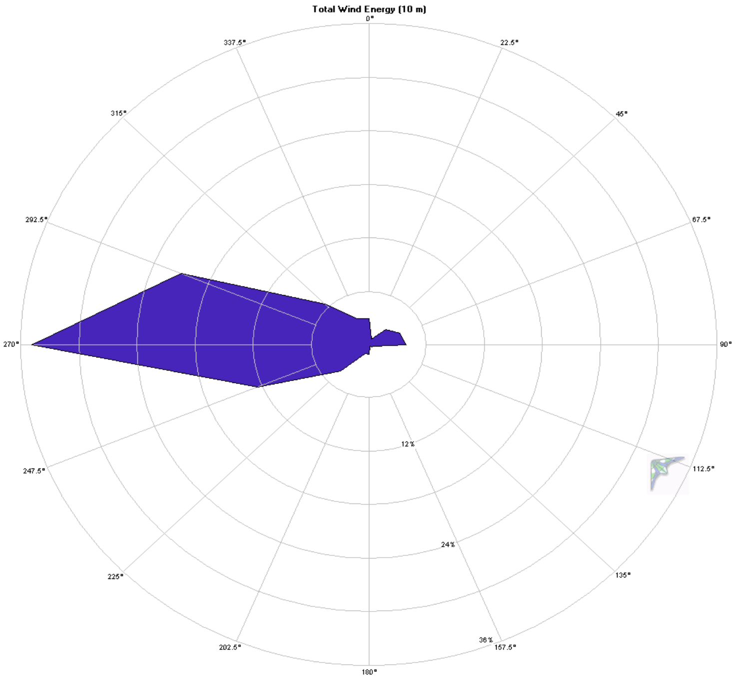


Figure G.5 Total energy distribution at Hanimadhoo from 2003-2007. The axis shows values in % based on 16 angular sectors.

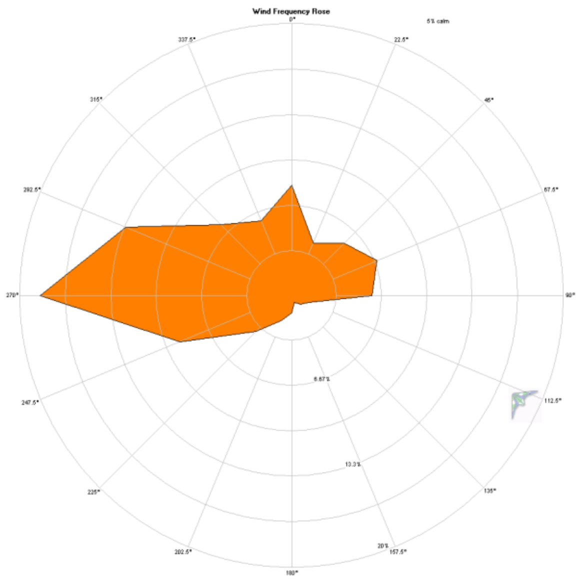


Figure G.6 Wind frequency rose at Hanimadhoo from 2003-2007. The axis shows values in % based on 16 angular sectors.

G9: At Hulu'le Weather Station

Hulu'le weather station is located at Male' international airport. Figures G.7 to G.12 demonstrate the important findings in graphical form from the wind analysis of data at Hulu'le weather station.

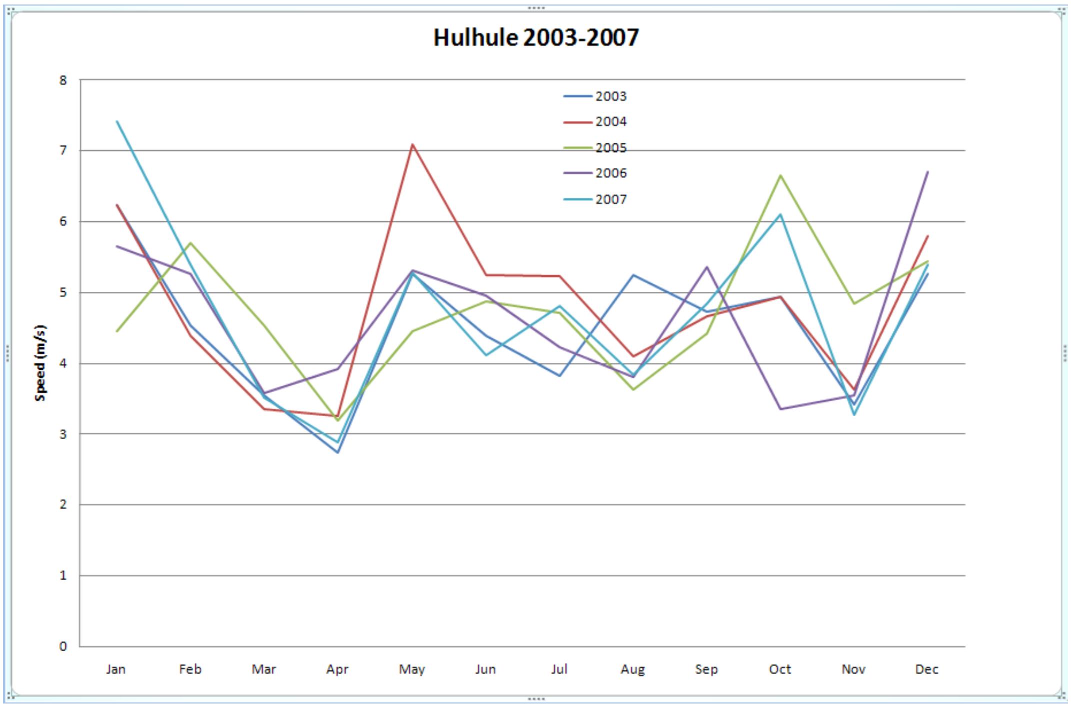


Figure G.7 Hulu'le average wind speeds over five years

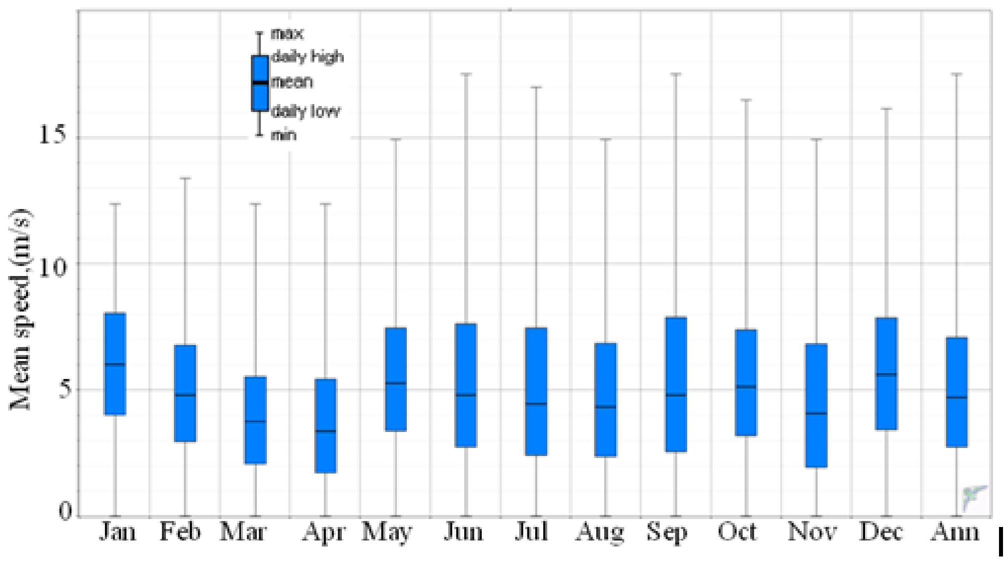


Figure G.8 Monthly mean wind variations at Hulu'le from 2003-2007

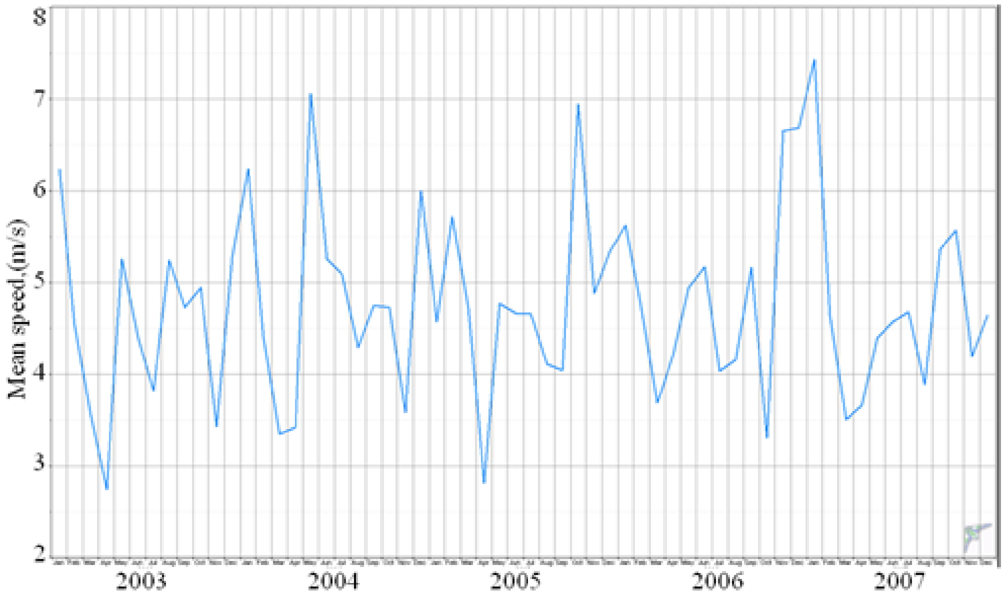


Figure G.9 Monthly mean wind speed at Hulu'le from 2003-2007

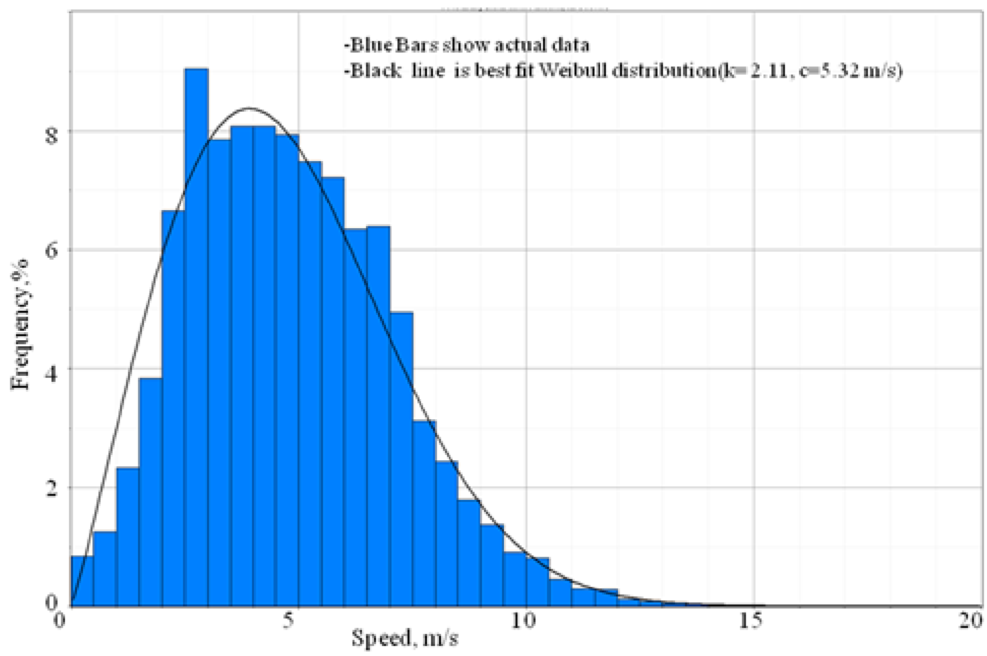


Figure G.10 Probability distribution function of wind speed at Hulu'le from 2003-2007

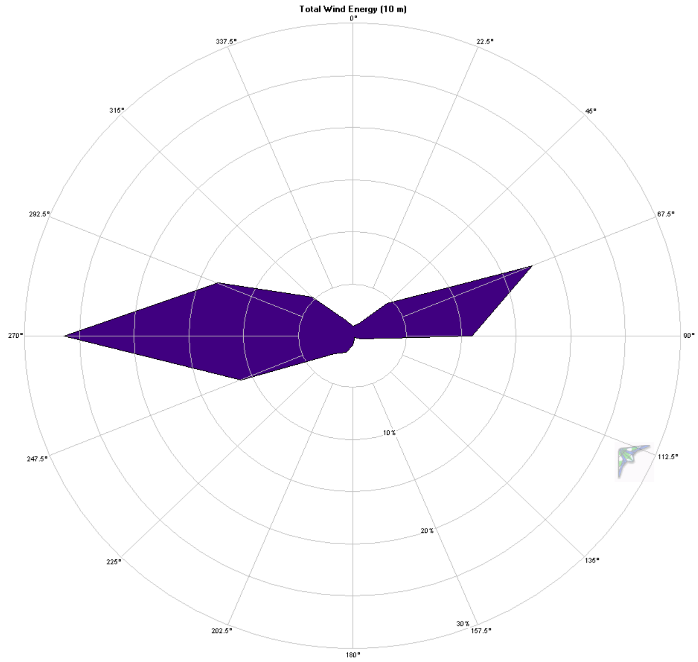


Figure G.11 Total energy distribution at Hulu'le from 2003-2007. The axis shows values in % based on 16 angular sectors.

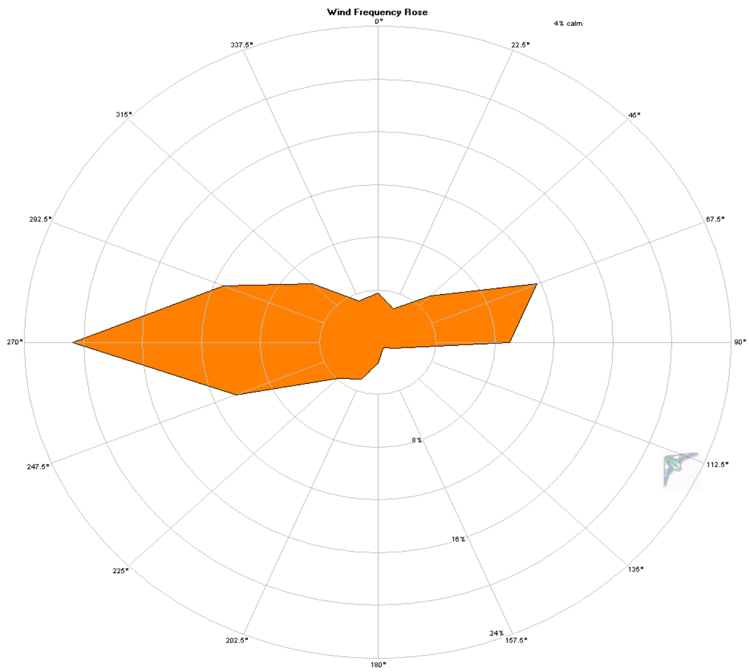


Figure G.12 Wind frequency rose at Hulu'le from 2003-2007. The axis shows values in % based on 16 angular sectors.

G10: At Kadhdhoo Weather Station

Figure G.13 to Figure G.16 demonstrate the important findings in graphical form from the wind analysis of data at Kadhdhoo weather station

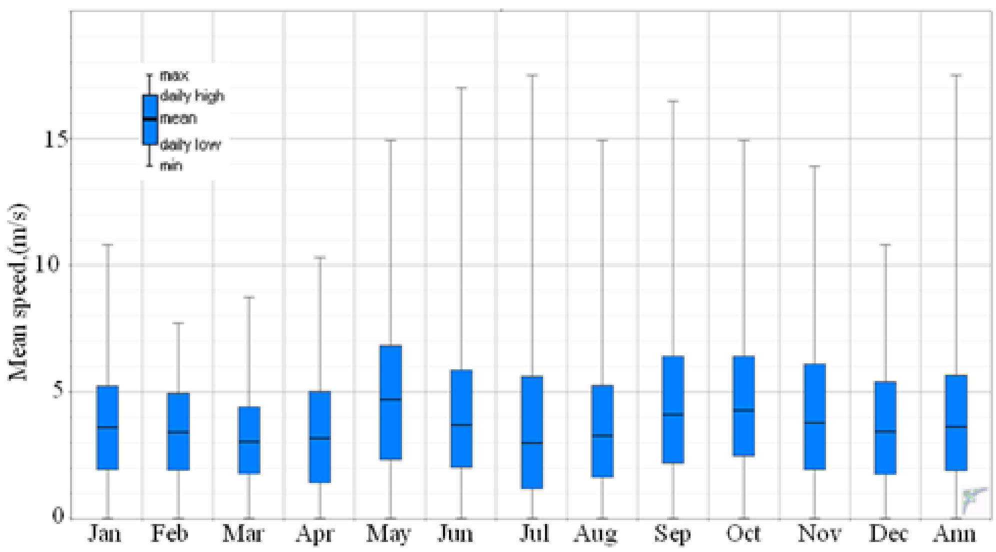


Figure G.13 Monthly mean wind variations at Kadhdhoo from 2003-2007

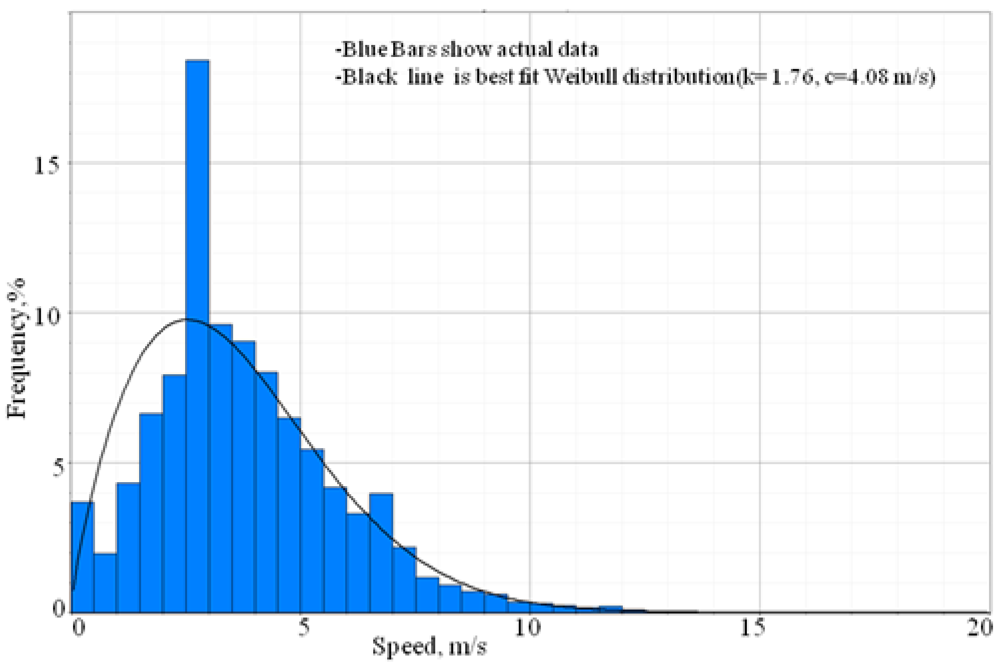


Figure G.14 Probability distribution function of wind speed at Kadhdhoo from 2003-2007

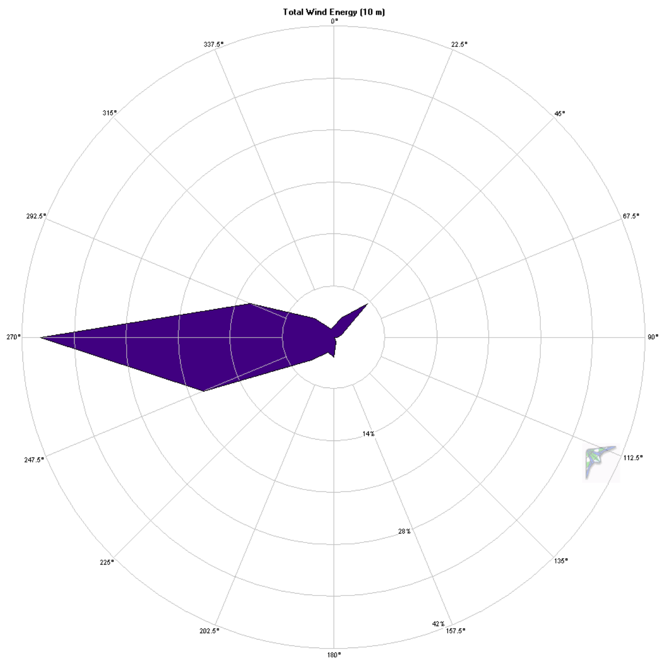


Figure G.15 Total energy distribution at Kadhdhoo from 2003-2007. The axis shows values in % based on 16 angular sectors.

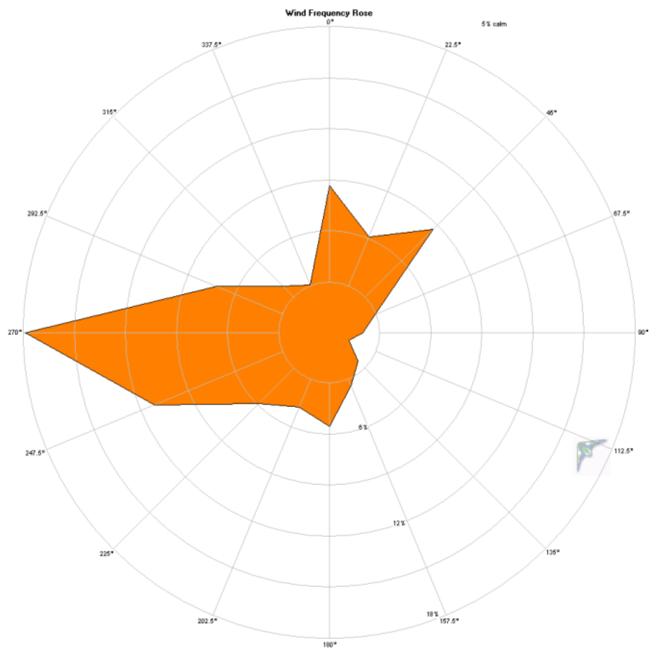


Figure G.16 Wind frequency rose at Kadhdhoo from 2003-2007. The axis shows values in % based on 16 angular sectors.

G11: At Kaadedhdhoo Weather Station

Figures G.17 to G.20 demonstrate the important findings in graphical form based on the wind analysis of data at Kaadedhdhoo weather station.

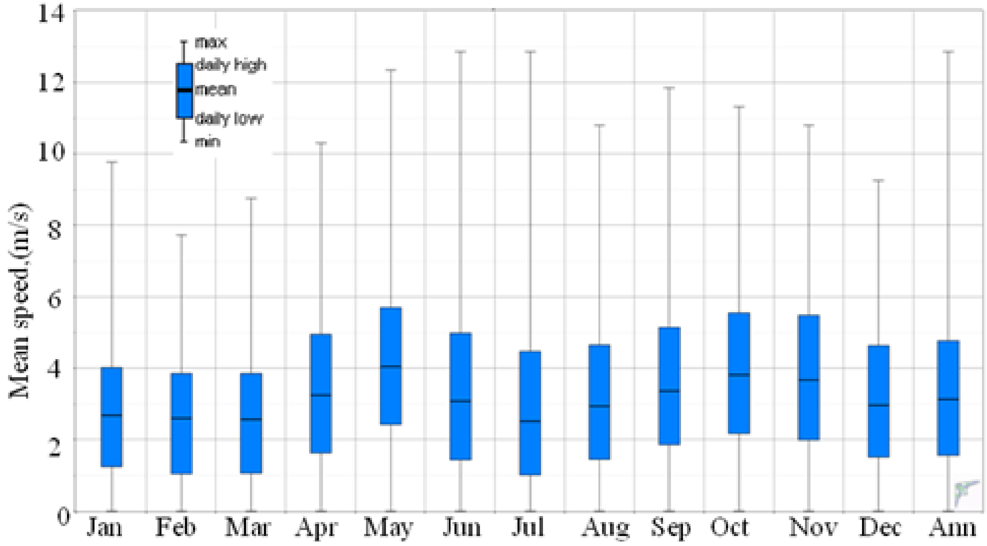


Figure G. 17 Monthly mean wind variations at Kaadedhdhoo from 2003-2007

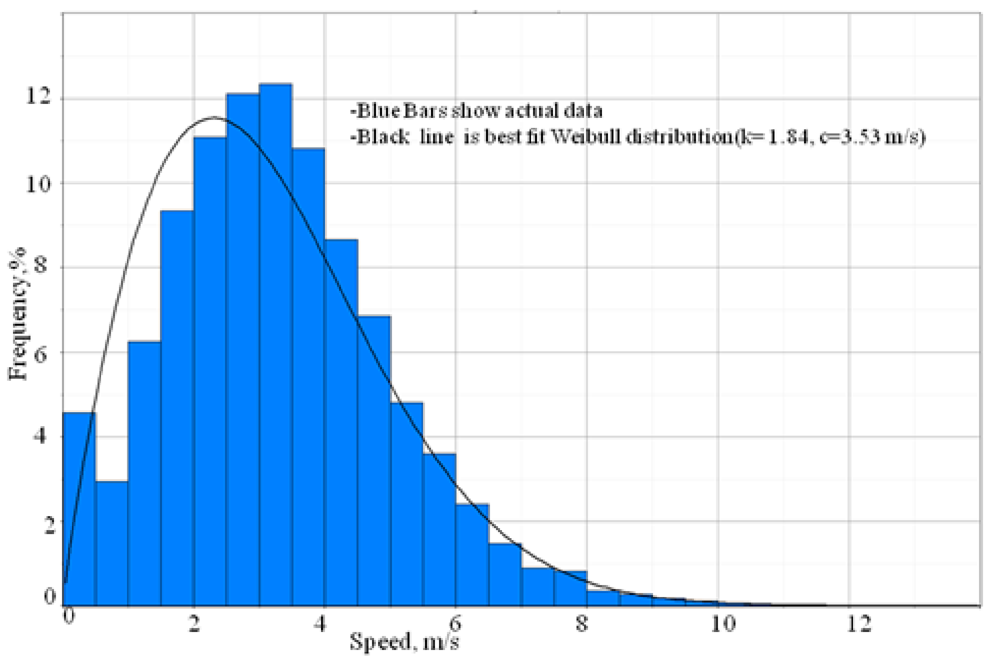


Figure G.18 Probability distribution function of wind speed at Kaadedhdhoo from 2003-2007

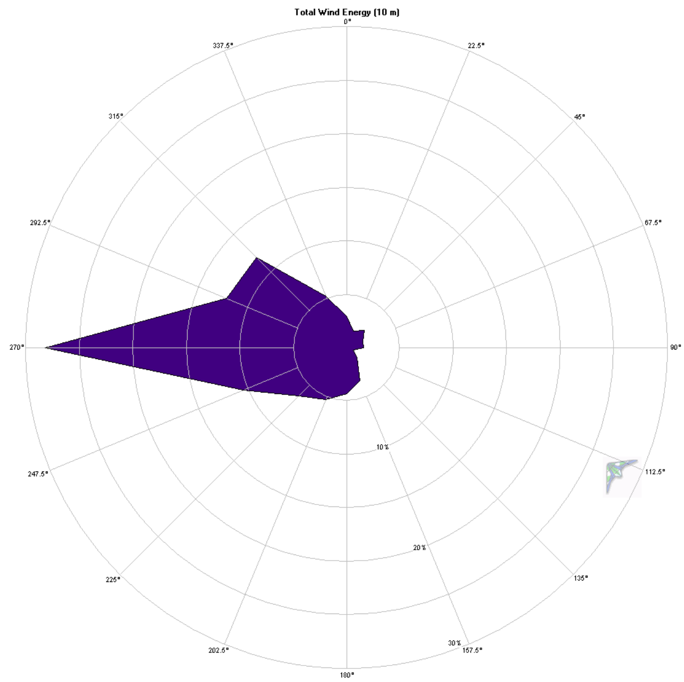


Figure G.19 Total energy distribution at Kaadedhdhoo from 2003-2007. The axis shows values in % based on 16 angular sectors.

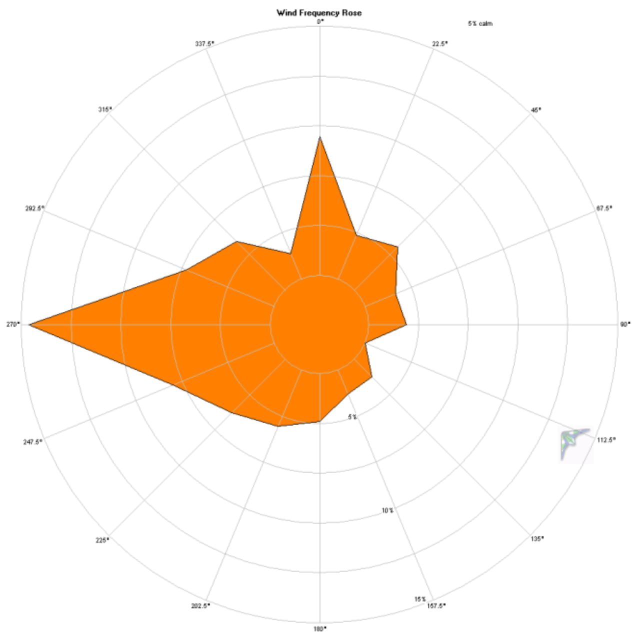


Figure G.20 Wind frequency rose at kaadedhdhoo from 2003-2007. The axis shows values in % based on 16 angular sectors.

G12: At Addu Gan Weather Station

Figures G.21 to G.24 demonstrate the important findings in graphical form from the wind analysis of data at Gan weather station.

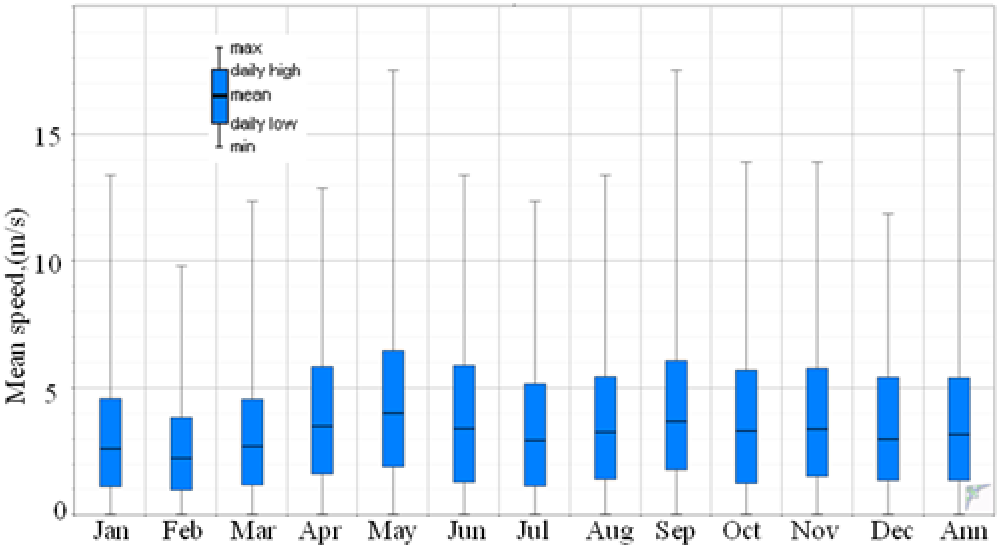


Figure G.21 Monthly mean wind variations at Gan from 2003-2007

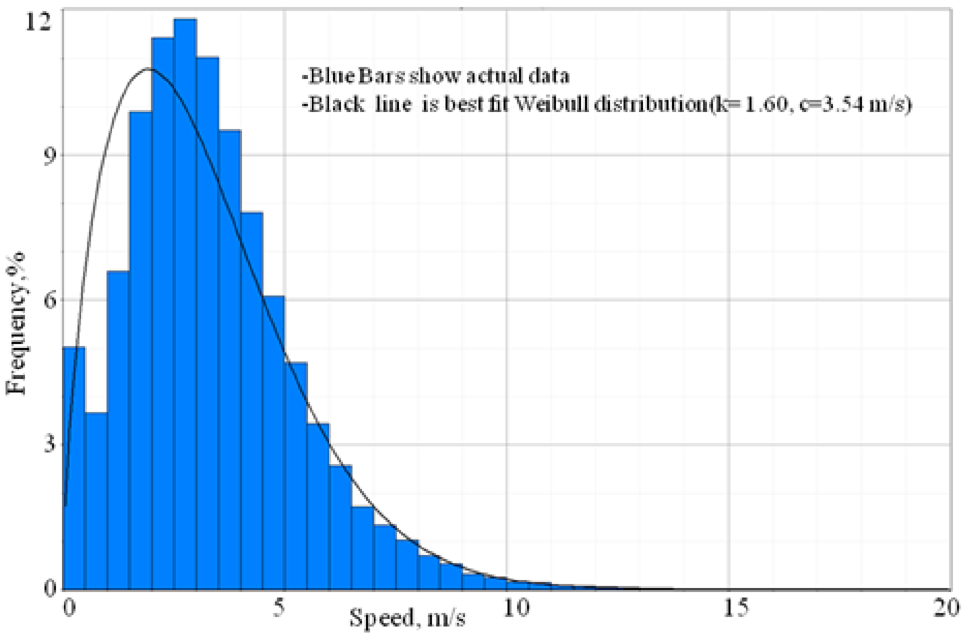


Figure G.22 Probability distribution function of wind speed at Gan from 2003-2007

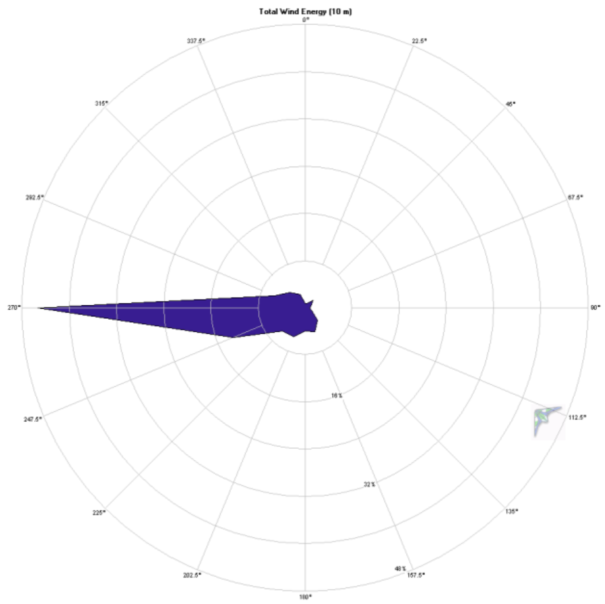


Figure G.23 Total energy distribution at Gan from 2003-2007. The axis shows values in % based on 16 angular sectors.

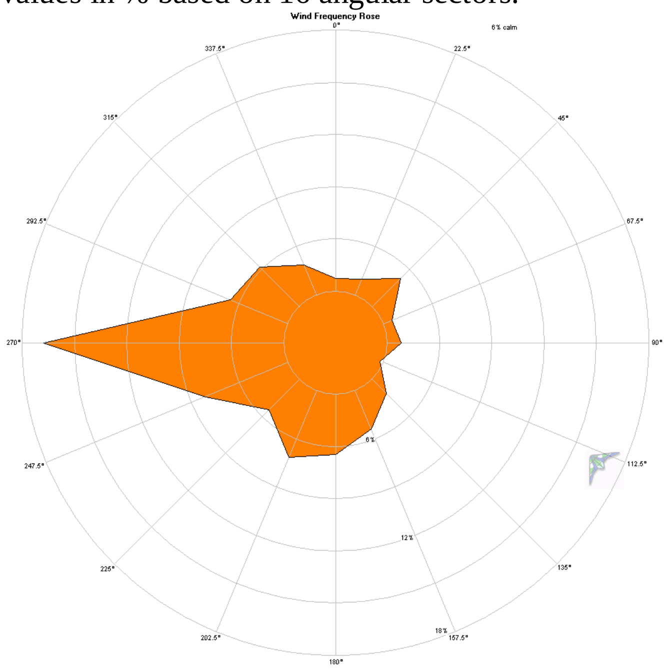


Figure G.24 Wind frequency rose at Gan from 2003-2007. The axis shows values in % based on 16 angular sectors.

G13 Maximum Wind Speeds

Figure G.25 shows the three hourly maximum wind speeds between 2003 and 2007 at Hulu'le weather station. Addressing the peak wind speeds and frequency is important when analysing the risks posed to the wind turbines. As seen from the five year peaks the speed recorded has never been over 30m/s and only 3 of these recorded speeds are between 25m/s and 30m/s. On the basis of this, it could be said that there is no major risk that the wind turbines will be damaged or destroyed by excessive wind speeds.

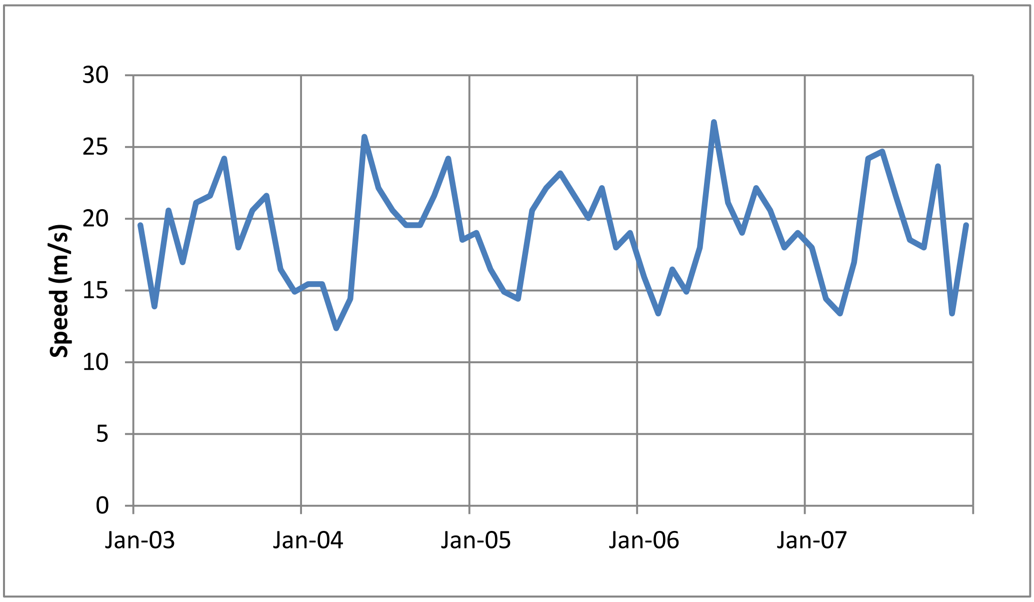
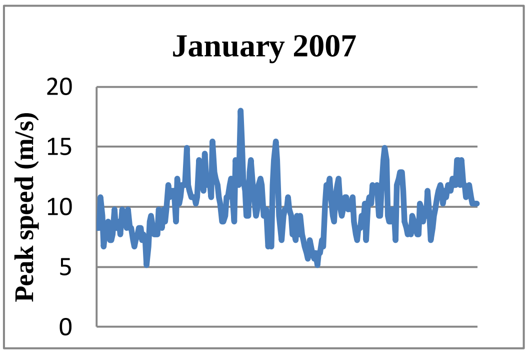
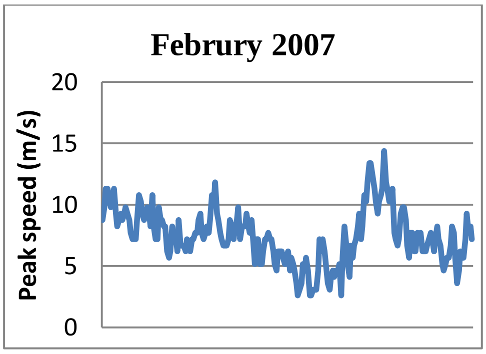
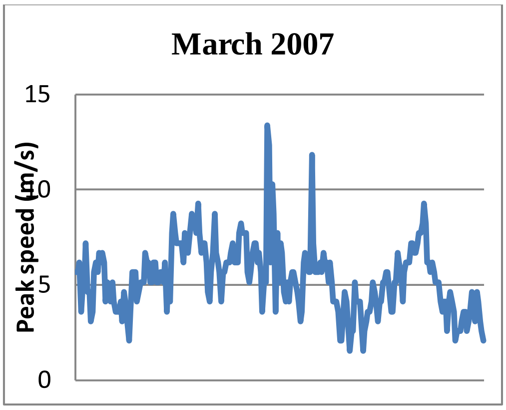


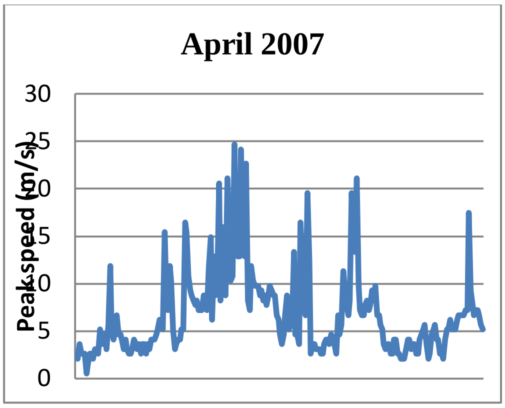
Figure G.25 Maximum wind speeds at the central weather station, from 3 hour maximum recordings.

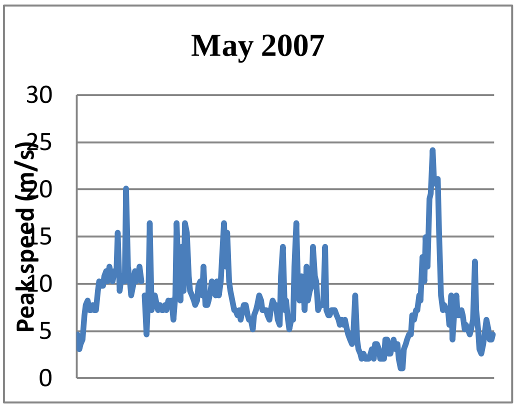
The following are the individual monthly peaks recorded as three hour maximum wind speeds. Plots for 2007 have been included to show the pattern.

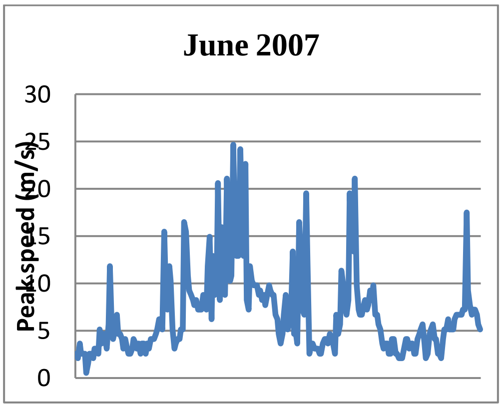


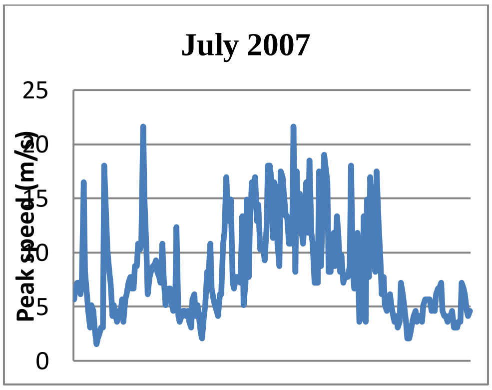


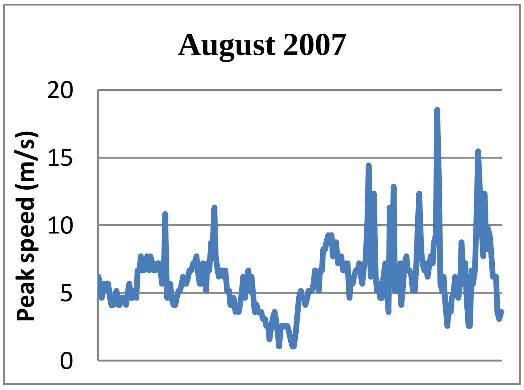

March 2007
Peak speed (m/s)
15
10
5
0

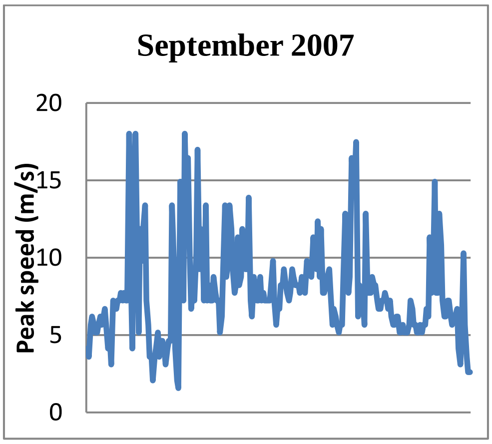

April 2007
Peak speed (m/s)
30
25
20
15
10
5
0

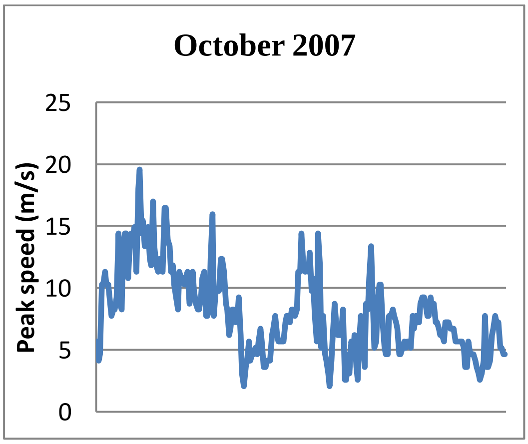

May 2007
Peak speed (m/s)
30
25
20
15
10
5
0

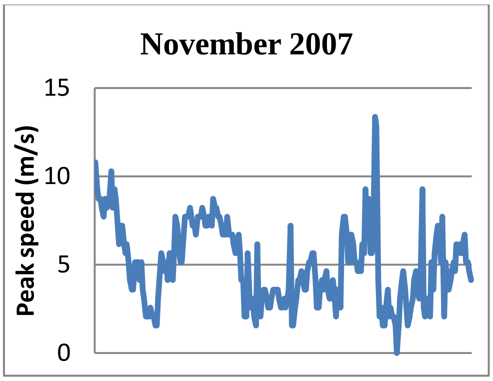

June 2007
Peak speed (m/s)
30
25
20
15
10
5
0

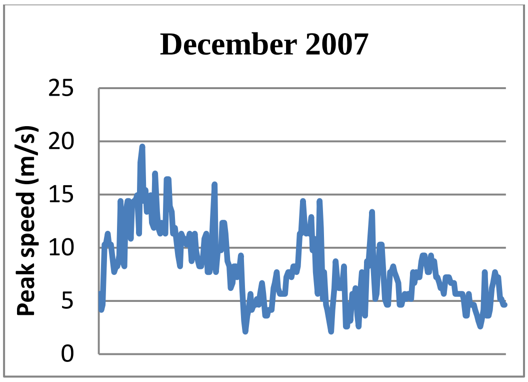

July 2007
Peak speed (m/s)
25
20
15
10
5
0


August 2007
Peak speed (m/s)
20
15
10
5
0


September 2007
Peak speed (m/s)
20
15
10
5
0


October 2007
Peak speed (m/s)
25
20
15
10
5
0





The maximum wind profiles of the years 2003 to 2006 have no significant changes from that of 2007 in terms of severity and length.

Appendix H: Power Generation in Capital City (Male')

The State Electric Company Ltd (STELCO) is a state-owned organization and is responsible for the generation, distribution and supply of electricity to customers on Male'. STELCO has a modern diesel power generating plant in Male'. The company started providing electricity with just one 14 kW generator set in 1949, when it was known as the Electricity Department and later the Maldives Electricity Board (MEB). Since then the organization's generation capacity has increased according to the demand of consumers through various expansion projects. The powerhouse is the largest generation facility in the Maldives. The generation facility has a total capacity of 38 MW, which at present requires over 126,000 liters of diesel for daily operations.

H1: Load characteristics

The load characteristics of the demand system are of great importance for the optimization of the supply system. For instance, if the peak load is demanded in the evening (due to lighting needs), as is the case with Fenfushi and other remote islands, it is impossible to use direct solar energy in order to meet this peak demand. On the other hand, the peak load could be partly met by a battery, which is charged during the day by the PV panels. The typical daily load patterns for Male' on August 12, 2008 (Figure G.20) and for the Fenfushi Island on an average August 2008 day (Figure H.21) are presented. The load curve of Fenfushi is assumed to be typical of other remote islands in shape and this load curves differs significantly to that of Male'. Two major differences found are:

- The energy consumption per capita is almost 5 times higher than on the remote islands.
- The load curve is flatter, because of the high electric energy demand during public and private office hours and business (shops). This is mainly caused by the high penetration of air conditioning systems in multi-storey buildings in Male', where air conditioning units are used during the hot and humid midday hours.

Figure H.22 shows the annual maximum demand of the capital city from 1987 to 2007 in megawatts (MW) and Figure H.23 shows the total electrical energy generated during the same period in kWh. Figure H.24 shows the diesel fuel consumption for electricity generation. The number of kWh generated per litre of diesel fuel varies from 3.11 to 4.02 throughout this twenty year period. Based on the 2007 values it is estimated that one litre of lubricating oil is used for every 286 litres of diesel fuel.

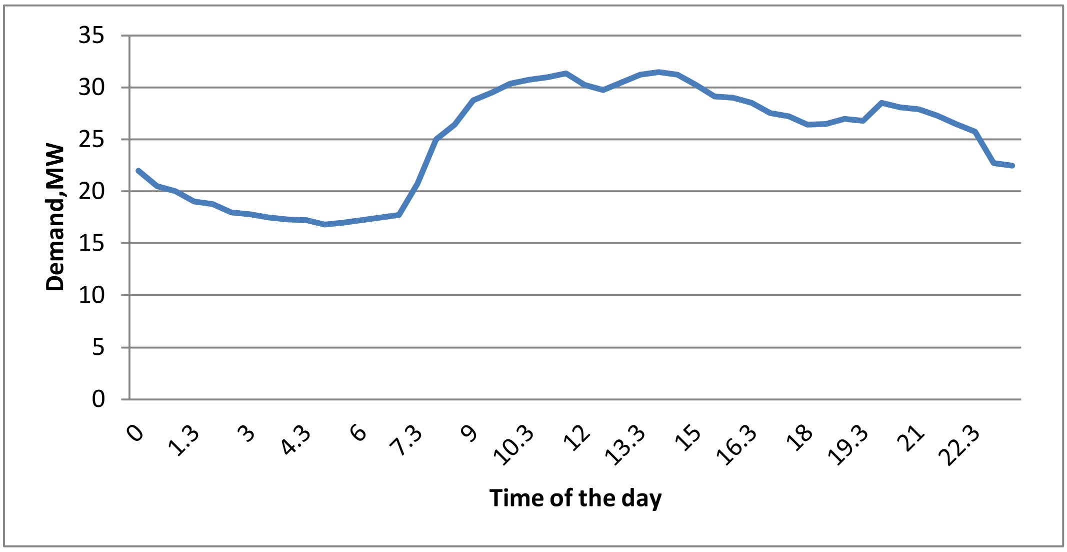


Figure H. 20 Typical daily load profile for Male'

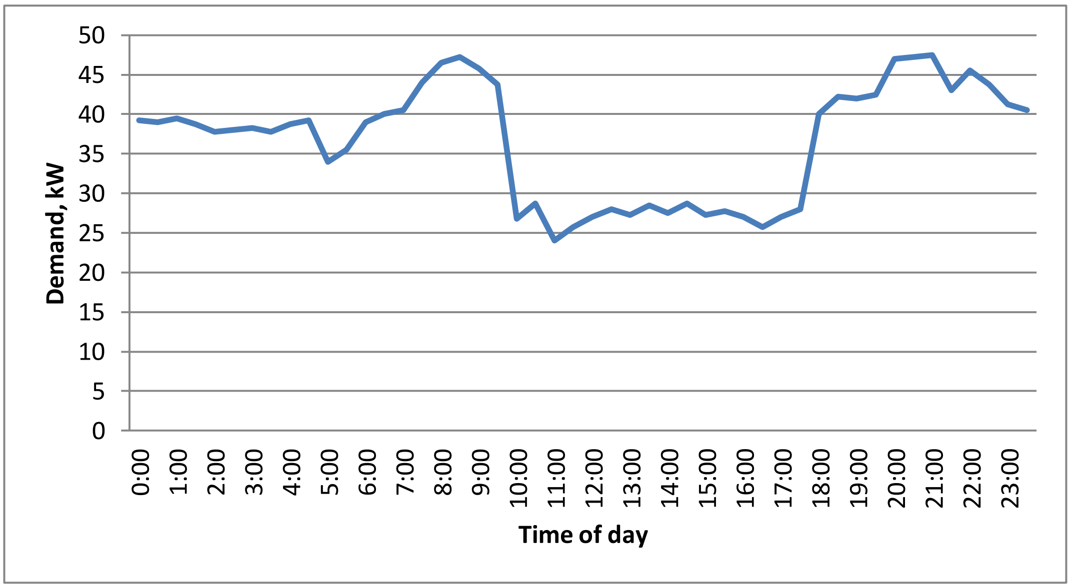


Figure H.21 Fenfushi load curve for a typical day

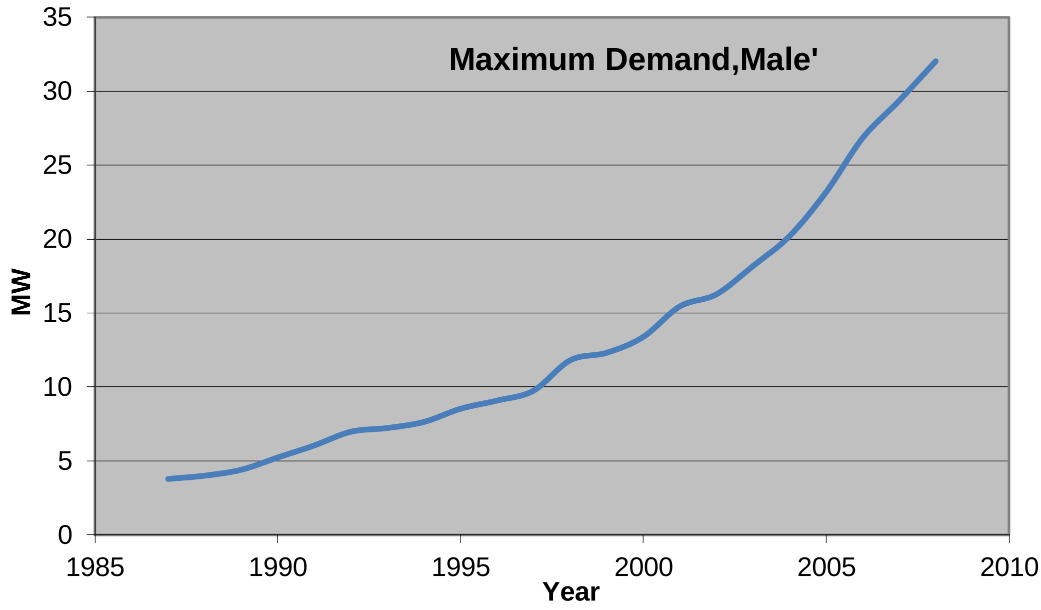


Figure H.22 Annual maximum demand from 1987-2007

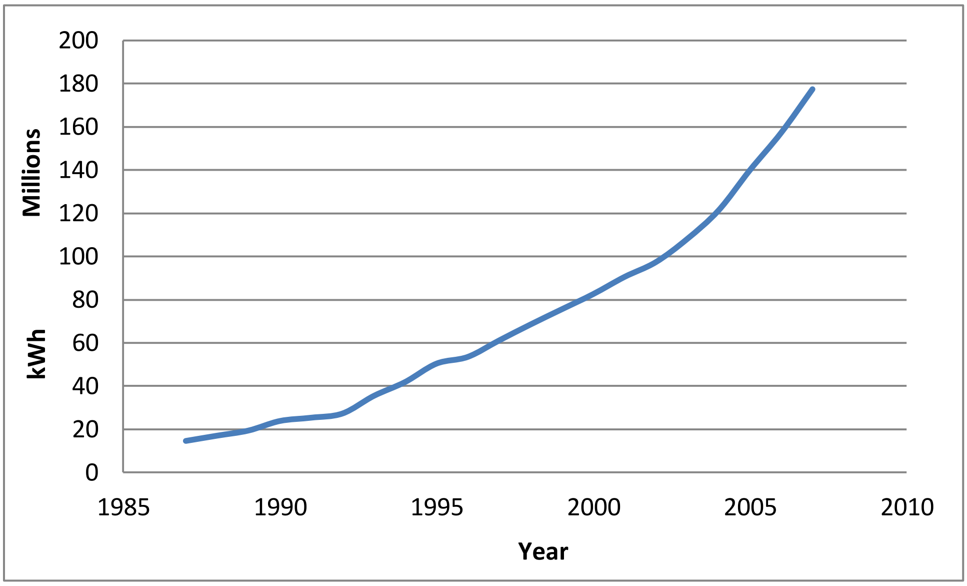


Figure H.23 Annual electrical energy generated from 1987-2007

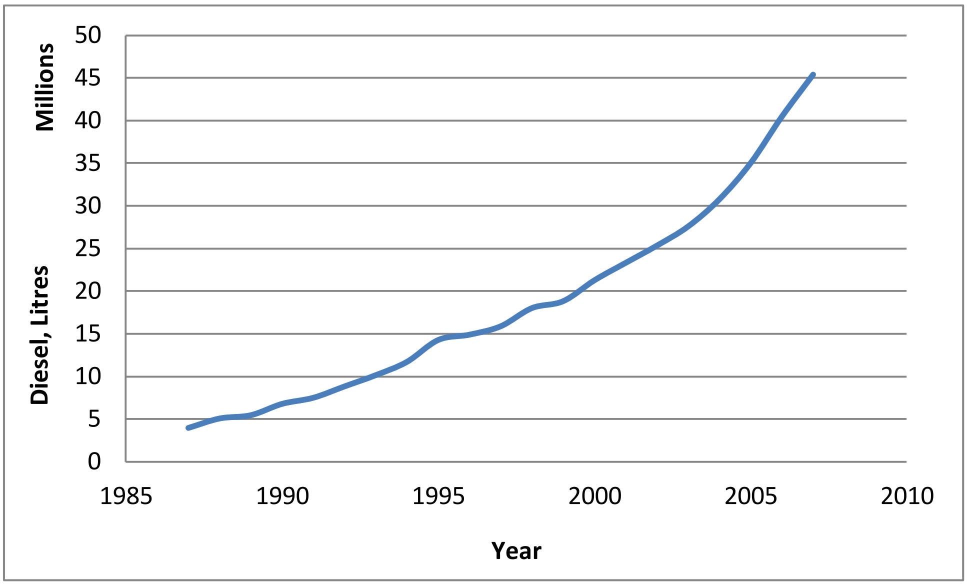


Figure H.24 Annual diesel fuel consumption from 1987-2007